LINKING INTEROPERABILITY CHARACTERS AND MEASURES OF EFFECTIVENESS: A METHODOLOGY FOR EVALUATING ARCHITECTURES

GRADUATE RESEARCH PROJECT

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AFIT/ISE/ENV/09-J01

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Wright-Patterson Air Force Base, Ohio

AFIT/ISE/ENV/09-J01

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GRADUATE RESEARCH PROJECT

Presented to the Faculty

Department of Systems Engineering

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Systems Engineering

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June 2009

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AFIT/ISE/ENV/09-J01

Abstract

The Air Force Research Laboratory's Sensors Directorate has crafted a long-term layered sensing project and seeks a method by which to compare different architectural representations. This research provides an executable methodology for quantitative architecture comparisons based on interoperability characters and measurements. The methodology has two components and is demonstrated on an urban operations mission thread scenario. The layered sensing scenario requires a variety of sensor-equipped platforms to shift orbits while supporting a mission (e.g. supply convoy) reacting to unplanned events (e.g. improvised explosive device). The first component is a discrete event simulation capturing relevant sensor, platform, and mission operations and providing measures of effectiveness (MOEs) and measures of performance (MOPs). The second component is an application of a general purpose interoperability measurement technique applied to a specific scenario demonstrating blue on blue (collaborative) interoperability. The results from experimental component comparisons show that changes in interoperability measurements do not always reflect the magnitude of changes in mission effectiveness or system performance. For net-centric applications, changes in the number of process paths may be a better indicator for the degree of interoperability present in a given architecture.

Acknowledgments

We would like to express our sincere appreciation to our faculty advisors, Dr. David R. Jacques and Dr. John M. Colombi, for their guidance and support throughout the course of this research project. Their insight and experience was certainly appreciated. We would also like to thank our sponsor, Mr. Bruce Preiss, from the Air Force Research Laboratory for both the assistance and latitude provided to us in this endeavor. Lastly, we are grateful for the support provided to us by our families while we were working on this research effort.

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LINKING INTEROPERABILITY CHARACTERS AND MEASURES OF EFFECTIVENESS: A METHODOLOGY FOR EVALUATING ARCHITECTURES

1. Introduction

1.1 Background

The conflicts in Iraq and Afghanistan brought new challenges to an American military force largely designed to combat other conventional forces consisting of tanks, aircraft, ships, and large numbers of organized, readily identifiable troops. These challenges are highlighted by comparisons between the first and second Gulf Wars. During the first Gulf War in 1990 and 1991, US/coalition military doctrine, equipment, and personnel proved far superior to the similarly structured but ill-prepared Iraqi forces.

The current Iraqi conflict has proven to be more difficult than the first Gulf War. New challenges include fighting against insurgent groups that resort to unconventional tactics and terrorist-like activities. The US and her allies are fighting enemies that hide in a variety of difficult settings, including masquerading as civilians. Defeating these unconventional groups of fighters requires coalition forces to quickly adapt tactics and technologies. One series of adaptations grew into the concept of persistent surveillance. Fueled by new sensors, platforms, and command and control capabilities, persistent surveillance seeks as an ultimate goal total Area of Responsibility (AOR) coverage: all locations, 24 hours a day, 7 days a week, with the ability to spatially zoom-in or out with different sensors as mission needs dictate. (1:1-4)

Persistent surveillance requires highly interoperable sensors and platforms operating with a robust command and control backbone. Working in support of this concept, the Air Force Research Laboratory's (AFRL's) Sensors Directorate (RY) crafted a layered sensing architecture. Figure 1 shows an Operational View-1 (OV-1) for the architecture. An AFRL white paper describes layered sensing in the following manner:

> "Layered Sensing provides military and homeland security decision makers at all levels with timely, actionable, trusted, and relevant information necessary for situational awareness to ensure their decisions achieve the desired military/humanitarian effects. Layered Sensing is characterized by the appropriate sensor or combination of sensors/platforms, infrastructure and exploitation capabilities to generate that situation awareness and directly support delivery of "tailored effects"." (1:ii)

Table 1 captures important characteristics for potential layered sensing platforms and sensors which are shown in Figure 2 through Figure 5.

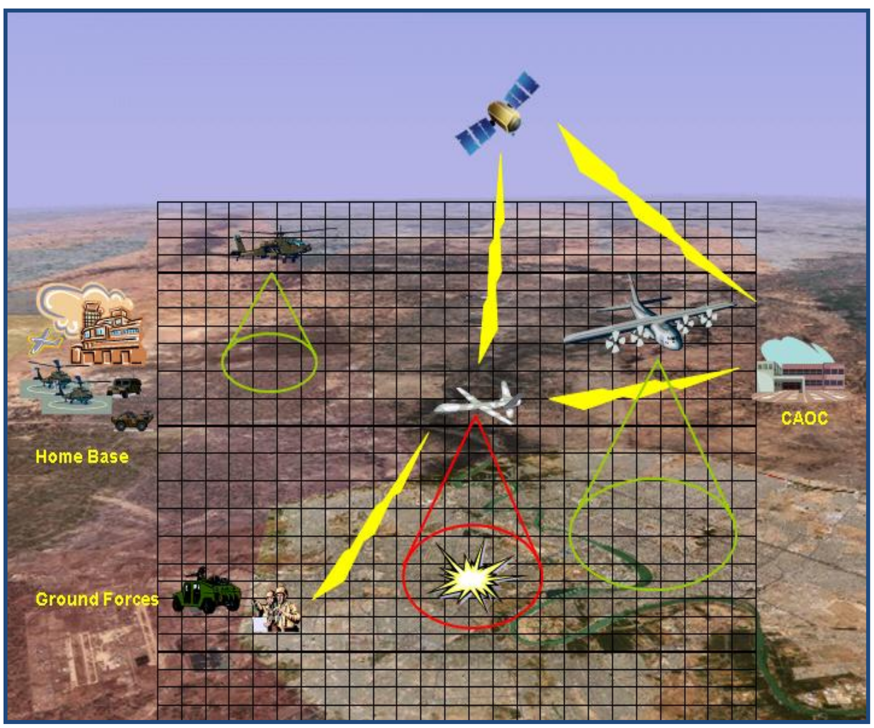


Figure 1. Layered Sensing OV-1

Table 1. Layered Sensing Systems

Platform	Sensor	Description
Lair	E/O	Twin prop engine, fixed wing aircraft, E/O sensor with 4-km radius Field of View (FOV), and 7-hr mission time
Argus-IS	E/O	Single engine, rotary wing unmanned aerial vehicle, E/O sensor with 3-km radius FOV, and 20-hr mission time
Gotcha	SAR	ISR pallet aboard fixed wing cargo aircraft (i.e. C-130), SAR sensor with 20-km radius FOV, 6-hr mission time
Nitestare	IR	Twin prop engine, fixed wing aircraft, IR sensor with 5-km radius FOV, and 7-hr mission time
Generic	E/O, IR, SAR	Twin prop engine, fixed wing unmanned aerial vehicle, E/O, IR, and SAR sensors with 10-km radius FOV, and 10-hr mission time

AFRL/RY seeks a method by which to compare different layered sensing architectures as part of the on-going developmental effort. Useful architecture comparisons will aid acquisition decision making as layered sensing evolves towards an initial fielding in the 2015 timeframe. The Sensors Directorate desire for a quantitative comparison methodology provided another opportunity for Air Force Institute of Technology (AFIT) participation in layered sensing research.

The AFIT Department of Systems and Engineering Management (AFIT/ENV) recently published a dissertation that hypothesized a novel technique for measuring interoperability across a broad spectrum of systems and applications (Ford, 2008). The dissertation sample applications focused on confrontational interoperability (blue system interoperability with or against red systems). The results of the research were intriguing, and AFIT/ENV wished to further test the technique by incorporating scenarios that measured collaborative interoperability (blue system interoperability with other blue

systems). An AFRL/RY desire to evaluated layered sensing architectures coupled nicely with the AFIT/ENV interest in additional testing of Ford's technique.

Figure 2. Lair/Nitestare: C-12 Huron (Electro-optical and Infrared Sensors)

Joint doctrine provides a concise definition of interoperability: it is "the ability to operate in synergy in the execution of assigned tasks." (2:2) The definition can be expanded: "the condition achieved among communications-electronics systems or items of communications-electronics equipment when information or services can be exchanged directly and satisfactorily between them and/or their users." (2:2) Obtaining a general definition is a necessary first step; however, providing specific examples of worthwhile interoperability and quantitatively measuring impact on mission effectiveness is more challenging.

1.2 Problem Statement

The research addresses this fundamental problem: can changes in architecture be quantitatively linked to changes in mission effectiveness? The research focus is narrowed down to only those changes in architecture which relate to measurements of interoperability. The primary approach for solving this problem links changes in interoperability measurements (elements of architectural designs) to changes in measures of effectiveness (MOEs) or performance (MOPs) through discrete event simulation.

1.3 Research Hypothesis/Questions/Objectives

This section presents the graduate research project hypothesis. The hypothesis is fleshed out with an accompanying set of questions that bound the research and objectives that focus work on specific goals.

1.3.1 Hypothesis

AFIT asserts that MOE values characterizing the performance of a collection of systems will vary as a function of the set of interoperability characters inherent to that collection of systems. Further, the addition of new interoperability characters will affect the MOE values that objectively describe the collection of systems. Lastly, the effect of a new interoperability character may be positive or negative, depending upon its influence on the collection of systems. Said another way, more interoperability may not always be good.

1.3.2 Questions

The questions that bound the research are:

1. Can a collection of systems be at least partially characterized by their collaborative interoperability characters?

2. Can the interoperability measurement methodology derived by Ford in 2008 be executed for scenarios demonstrating collaborative interoperability?

3. Will the interoperability characterization manifest itself in a set of MOEs, the values of which are calculated by a discrete event simulation?

4. Can a discrete event simulation adequately capture the significant operational characteristics of a scenario drawn from a mission thread of interest to AFRL/RY?

5. Can a methodology be crafted to support future AFRL/RY architectural decision making?

Figure 3. Argus-IS: A-160 Hummingbird (Electro-optical Sensor)

1.3.3 Objectives

The objectives that focused the research are:

1. Execute Ford's methodology for scenarios incorporating collaborative interoperability.

2. Identify an operational mission thread and a specific scenario relevant to AFRL/RY interests.

3. Build a discrete event simulation that adequately captures relevant mission thread and scenario characteristics.

4. Identify a set of interoperability characteristics that adequately capture current and potential future layered sensing attributes.

5. Incorporate appropriate systems engineering principles learned throughout the AFIT Intermediate Developmental Education (IDE) program. Develop static and dynamic representations of layered sensing in order to lay the foundation for a discrete event simulation.

6. Determine a set of MOEs that demonstrate adequate traceability and capture relevant layered sensing performance.

7. Capture values for these MOEs (done with the discrete event simulation)

8. Demonstrate a link between interoperability characters and MOEs.

1.4 Methodology

The research methodology has two components and is demonstrated on an urban operations mission thread scenario. The scenario requires electro-optical (E/O), infrared (IR), and synthetic aperture radar (SAR) sensor-equipped platforms to shift orbits while

supporting a mission (e.g. supply convoy) reacting to an unplanned event (e.g. improvised explosive device planted along the convoy route of travel). The scenario was selected from three use cases developed during discussions with AFRL/RY. The selected scenario is a case of high interest to both the sponsor and the researchers.

Figure 4. Gotcha: ISR Pallet aboard a Cargo Aircraft (e.g. C-130) (SAR Sensor)

The first methodology component captures relevant sensor, platform, and mission operations. The primary simulation outputs are MOE and MOP values. The MOEs and MOPs are drawn from the AFRL layered sensing attributes. The foundation of the discrete event simulation rests on static (object diagram) and dynamic (sequence diagram) representations of the selected use case. An operational activity model was also developed to seed the simulation effort.

The second component is the interoperability measurement technique developed by Ford in 2008. In this case, the research attempts to link collaborative interoperability measures to MOEs. The measurement approach identifies interoperability characters in the layered sensing architecture, links the various characters in a matrix calculation, and calculates the so-called measure of interoperability. Different layered sensing architectures will have different sets of interoperability characters. As such, the technique will produce a different interoperability measure for each sensing architecture.

Experimentation shows the two methodology component results may indeed be linked. When the linkage is present, it occurs between the discrete event simulation-calculated MOE and MOP values and the interoperability measurement made by Ford's technique. Further, as interoperability characters are added to both the interoperability measurement matrix and the discrete event simulation, the MOE and MOP values change in ways that do not always correlate well with interoperability measurements. More to the point, the addition of interoperability characters that show small increases in interoperability measurements may cause substantial changes in MOE and MOP values. In other cases, there is no quantifiable linkage between interoperability measurement and MOE or MOP value. Although not conclusive, the set of numerical experiments examined during this research does further define the relationship between changes in interoperability and measures of mission effectiveness.

1.5 Assumptions/Limitations

There are a number of assumptions associated with the research approach that bound the conclusions and implications reached during the project. The most important assumptions and their accompanying limitations are summarized in this section.

The concept of interoperability measurement is both diverse and complex. As such, a series of important assumptions were made to scope the research down to a manageable, yet still useful and interesting, level of effort. The first scoping decision was selecting an urban mission thread instead of a rural mission thread, the assumption being that urban mission threads were both more challenging for layered sensing applications and more interesting to the research sponsor.

Once an urban mission thread was selected three specific use cases were developed in conjunction with the AFRL sponsor. One of these use cases centered on a blue force reaction to an unplanned event. The reaction to an unplanned event was selected because the researchers assumed it was both the most interesting and the most stressing of the three scenarios for current layered sensing architectures.

There are limitations associated with the scoping effort. The most significant is that selection of an urban mission thread removed hyperspectral sensors from inclusion in the discrete event simulation. Although worth noting, this limitation has no impact on the conclusions reached after examining the numerical experiments.

More assumptions were made regarding the types of sensors and platforms included in the discrete event simulation. Specifically, three sensor types were selected: E/O, IR, and SAR. Although layered sensing could ultimately incorporate a large

number of different sensor types, the three selected provided enough flexibility to deal with challenges presented during simulated missions (e.g. day versus night, good weather versus bad).

Figure 5. Notional MQ-X Reaper-like Unmanned Arial Vehicle (Multiple Sensors)

The number of platform types was capped at five. There is no cap for total number of platforms, just for different types. Five platform types coupled to three sensor options demonstrate that the quantitative architecture comparison methodology is viable even if every possible future manifestation of layered sensing cannot be mimicked in the current simulation. These sensor and platform assumptions were made specifically to simplify the discrete event simulation.

A spatial construct was needed for the simulation. To address this need, the researchers used a grid composed of keypads (individual squares in the grid) to represent the mission space. Both keypad and grid size are inputs provided by the simulation user.

Although there are no upper or lower bounds programmed into the simulation, the numerical experiments were run with a keypad size of one square kilometer and a grid that measured 50 by 50 keypads (50 by 50 kilometers). A spatial construct of this nature corresponds well to the actual size of an urban area of interest, is large enough to incorporate various sensor footprints, allows for a range of distances between sensors and the location of interest, and is appropriately scaled for ranges of typical ground missions. Even though the space over which the simulated sensors and platforms operate is limited, the limitation does not detract from either the numerical experimentation or the results derived from it.

The simulation starts with the unplanned event to which the mission must respond. Once started the simulation runs for 24 hours and the run time does not change from one run to the next. Most missions of the type mimicked in the simulation would not last 24 hours. This departure from reality is tolerated because the simulation length was selected to stress layered sensing architectures. Specifically, the 24-hour mission length greatly exceeds loiter time for the platforms in the AOR at the time the unplanned event occurred. This timing epoch all but forces layered sensing architectures to reconstitute platforms and sensors in order to cover the entire mission. Further, transitions between day and night, which force architectures to blend sensor types or suffer in the MOE-based performance measurement, have been modeled as well.

The simulation has a key decision point early in each run: select sensor and platform combinations in the AOR at the time of the unplanned event to respond to the event (shift orbits to ensure the event location falls within the sensor footprint). After this

decision is made, any new platform tasked to cover the mission comes from its respective home airfield. In other words, platforms in the AOR not initially selected to cover the event are not later tasked to backfill platforms as loiter times expire. This condition would not hold in most real contingency scenarios. In the simulation, it is assumed that these platform/sensor combinations are allocated to other missions and cannot be retasked after the initial tasking decision is made. This limitation was adopted because it is more stressing for layered sensing architectures. It requires platforms to travel farther distances or boast longer loiter times. The assumption also implies a heavier than normal tasking load.

The simulation has a user interface. The interface is an Excel spreadsheet that requests input for a number of variables needed to run the simulation. For example, the user can select both the total number of platforms and platform types (as long as types do not exceed five). The user can also select certain platform performance factors like speed. Others, like altitude, are not requested. Performance characteristics that play a role in architecture evaluation are requested from the user; those that do not influence the evaluation or are of no interest to the sponsor are not requested. So, although altitude impacts sensor ability to resolve targets, AFRL/RY assumes all platforms will be operating nominally at 20,000 ft MSL and sees no need to work altitude into the methodology.

All of the previously discussed simulation assumptions and limitations drive home one key point: the simulation is not reality. Creating a simulation that captures all aspects of the modeled use case accurately is well beyond the scope of this research. The

motivation for creating this simulation was modeling performance in a manner that allows for consistent MOE measurement while interoperability characters are varied during different experimental runs. The simulation is deemed a success as far as this limited goal is concerned.

There are many potential sources for interoperability characters relevant to the problem at hand. In order to properly constrain character selection, the researchers identified two primary motivations: relevancy to layered sensing and an appropriate level of Department of Defense (DoD) vetting. To accomplish both of these ends, characters from three Joint Capability Areas (JCAs) were used for experimentation: Battlespace Awareness, Command and Control, and Net-Centric. These three sources provided ample characters to use for experimentation and adequately addressed hypothesis requirements.

Lastly, the work done in this graduate research project retains all of the strengths and weaknesses, both known and unknown, of Ford's interoperability measurement methodology. No attempts were made to improve his technique, only to apply it to a specific collaborative interoperability scenario.

1.6 Implications

The research produced results supporting the following implications:

1. Ford's interoperability measurement technique can, in some cases, be used to relate collaborative interoperability to mission effectiveness measures.

2. Discrete event simulations can adequately capture the performance of a collection of systems and characterize this performance by capturing MOEs and MOPs.

3. Changing the interoperability characters present in a given collection of systems can be quantified by changes in interoperability measurements. Further, interoperability character changes can sometimes be linked to changes in MOE and MOP values.

4. Identifying interoperability characters in a given architecture and capturing resultant interoperability measurements (with Ford's technique and MOE values) allows for improving architecture designs by changing interoperability characters. Further, ranked comparisons can be made between different architectures performing the same mission.

The last implication lays the foundation for a quantitative architecture comparison methodology that can lend analytical rigor to future layered sensing acquisition actions undertaken by AFRL/RY.

1.7 Document Outline

This graduate research project report now proceeds to Chapter 2, which is a review of literature relevant to the work conducted over the last three academic quarters. Five pieces of literature (or at least literature-like information) were particularly important. Chapter 3 provides an in-depth treatment of the methodology used to conduct the numerical experiments and make the interoperability measurements. Chapter 4 presents the results of the experimentation and includes additional analysis done to properly scope the findings. The last chapter, Chapter 5, contains the conclusion and includes recommendations for further research.

2. Literature Review

2.1 Overview

Interoperability is a broad topic of interest to a number of diverse communities. As such, there is a substantial offering of literature describing different aspects of interoperability. It is impossible to capture all of the writing worthy of review in a single chapter. Instead, a summary of the most influential documents is provided. Each section briefly describes one source and explains its relevancy to the research.

2.2 Quantification of Interoperability – Early Thoughts

In May of 1989 Mensh, Kite, and Darby published an article in the Naval Engineers Journal that linked quantitative interoperability analyses to MOEs and MOPs. The analytical technique used to link interoperability to MOEs and MOPs rested on a depth of experience garnered from years spent working naval interoperability issues. The methodology presented in the paper was applied to an August 1987 Tactical Information Management Exercise. Although "elementary and based on fundamental principles," (7:251) the concept developed by these three researchers seeded several key ideas for the AFIT students.

First, defining "interoperability component" expanded the 1989 Joint Chiefs of Staff definition of interoperability in a manner supporting quantitative measurement and so enabled a precursor technique to the AFIT methodology developed by Ford in 2008. The concept of an interoperability component also likely influenced the AFIT definition of "interoperability character."

Second, Mensh et al linked quantification of interoperability to MOPs and, more important for the AFIT research, MOEs. This linkage is the linchpin upon which the AFIT interoperability comparisons are based.

Third, the Navy researchers calculated MOE values by using numerical simulations -- an approach emulated by AFIT.

Finally, Mensh and his partners used "basic truth table theory in conjunction with logic equations to evaluate the interoperability components." (7:251) This Boolean representation of interoperability (the component is either completely present or completely absent) is indeed basic. It is also appealing, elegant, and justifiable for some applications. The current AFIT research uses the same type of representation for the presence of interoperability characters and their impact to layered sensing architectures.

2.3 Layered Sensing

In 2008 AFRL/RY published a white paper called "Layered Sensing: Its Definition, Attributes, and Guiding Principles for AFRL Strategic Technology Development." This paper described the need for a layered sensing architecture due to the changing nature of irregular warfare and the current demand for Intelligence, Surveillance and Reconnaissance (ISR). To accomplish this mission, AFRL plans to develop technologies that will "certainly include various sensor systems, including audio, visual, chemical, biological, radio frequency, microwave, x-ray, infrared, ultraviolet, […] acoustic, and so on. Layered Sensing is characterized by the appropriate sensor or combination of sensors/platforms, infrastructure and exploitation capabilities." (1:11)

Clearly, the AFRL white paper is important because it describes what layered sensing is, at least as far as the Sensors Directorate is concerned. The paper, supplemented by conversations with the sponsor and other AFRL provided documentation, helped scope the research effort while keeping the project relevant to the Sensors Directorate mission.

For AFIT, one of the most important aspects of the AFRL white paper is the attributes that characterize layered sensing. These attributes are shown in Table 2. Pulling attributes from the AFRL paper that defines layered sensing provides traceability and ensures the selected attributes are well grounded in the customer's value system.

Table 2. Layered Sensing Attributes

Persistent Coverage*
Wide Area Coverage*
Assured Global Access
Engagement Quality Information
Timeliness*
Trusted Sensing
Information Triage
Robust, Agile, Adaptable*
Spectrum Dominance and Control*
Anticipatory Observations and Interactive Engagements
Tailored Performance
Affordable Open System Architecture

The MOEs used to gauge layered sensing performance must be linked to attributes. By providing validated attributes in their white paper, AFRL certainly facilitated AFIT efforts to derive MOEs relevant to layered sensing. The attributes marked with an asterisk in Table 2 are the attributes to which AFIT has linked MOEs. Table 3 shows the MOEs calculated during the simulation and the attributes to which they are linked.

Table 3. Attributes and Measures of Effectiveness

Attribute	Measure of Effectiveness
Persistent Coverage	- MOE 1: Percentage of time mission is covered by one sensor
Wide Area Coverage	- MOE 2: Percentage of the Area of Responsibility covered by sensors
Timeliness	- MOE 3: Time for information to pass from sensor to ground forces (fully processed upon arrival)
Robust, Agile, Adaptable	- MOE 4: Layered sensing mission failures in a 24-hour period - MOE 5: Average time taken to begin coverage after the unplanned event occurs
Spectrum Dominance and Control	- MOE 6: Percentage of time mission covered by at least two platforms

2.4 Measuring Interoperability

The authors used the aforementioned AFIT technique created by Ford in 2008 to measure interoperability. These measurements are one of the two sets of metrics used to evaluate and compare layered sensing architectures, so understanding the technique was an important part of the research effort. Also, one of the research goals was to demonstrate the feasibility of extending Ford's method to use collaborative interoperability measurements. Ford's dissertation provided the needed understanding and was a key reference throughout the project.

A short summary of Ford's technique shows several steps must be taken in order to produce a measurement value. First, the systems of interest must be identified. Next, an accompanying set of interoperability characters must be selected. The systems then need to be instantiated whereby a matrix (mating systems to characters) is populated with a Boolean representation of system capabilities based on which interoperability characters are present (although not used in this research project, Ford's technique can

also represent interoperability characters with real numbers). Once these steps have been accomplished, a measure of interoperability can be calculated. This is a simple application of Ford's method, but appropriate for the task at hand.

The derivation of the technique is involved, and will not be repeated here. Interested readers are directed to reference 6 (especially the third chapter) in the bibliography for a detailed treatment of the technique. Measurement calculations made during specific experiments are discussed in detail in Chapters 3 and 4 and Appendix A3.

2.5 Interoperability Characters

As stated earlier, a set of relevant interoperability characters must be identified in order to successfully execute Ford's methodology. These characters need to reflect some aspect of interoperability, must be either present in the modeled use case or capable of being added to it, and they should demonstrate traceability back to a vetted DoD source.

Three JCAs were identified that meet all of the above criteria. These JCAs are Battlespace Awareness, Command and Control, and Net-centric. The J7 under the Chairman of the Joint Chiefs of Staff maintains a list of JCA-related definitions on the Defense Technical Information Center's website (5). The specific interoperability characters used during research were drawn from this list and are shown in Table 4.

Table 4. Interoperability Characters

JCA Definition Number	Character
2	Battlespace Awareness
2.1	Intelligence, Surveillance, and Reconnaissance
2.1.2	Collection
2.1.2.3	Imagery Collection
2.1.2.3.1	Electro-Optical Imagery Collection
2.1.2.3.1.1	Panchromatic Imagery Collection
2.1.2.3.1.2	Infrared Imagery Collection
2.1.2.3.2	RADAR Imagery Collection
2.1.3	Processing/Exploitation
2.1.3.1	Data Transformation
2.1.3.2	Objective/Target Categorization
2.1.4	Analysis and Production
2.1.5	Intelligence, Surveillance and Reconnaissance Dissemination
5	Command and Control
5.5	Direct
5.5.2	Task
5.5.2.1	Synchronize Operations
5.5.2.2	Issue Plans
5.5.2.3	Issue Orders
6	Net-centric
6.1	Information Transport (IT)
6.1.2	Wireless Transmission
6.1.2.1	Line of Sight
6.1.2.2	Beyond Line of Sight

2.6 A Process for Providing Intelligence, Surveillance, and Reconnaissance Support

Joint Publication 2-01 (JP 2-01), Joint and National Intelligence Support to Military Operations, describes the process used to provide finished intelligence to US military forces. This doctrinal process description is important to the AFIT research because it provided a guide for constructing the simulation component that models how intelligence data passes from sensors through the Joint or Combined Air Operations Center (JAOC or CAOC) to the forces that require support. The interoperability-related

MOE used to gauge system performance is made in this part of the simulation, so a DoD-sanctioned process was an essential requirement for building a vetted simulation.

The JP 2-01 process has the following components:

1. Planning and direction
2. Collection
3. Processing and exploitation
4. Analysis and Production
5. Dissemination
6. Evaluation and feedback

The discrete event simulation incorporates components two through five. Both planning and direction and evaluation and feedback are beyond the scope of the current research.

In the use case simulated for this research, collection functions are performed primarily by the sensor and its accompanying platform. These functions potentially include target identification, coordination with other friendly forces, and prioritization of missions and resources.

Processing and exploitation may occur in the CAOC. So may analysis and production. The platforms that carry the sensors may also carry out these tasks. Functions performed by these components encapsulate the process of transforming raw data into finished intelligence. This includes merging data from multiple sources, integrating data with different formats, interpretation, analysis, coordination, and crafting the finished product into a medium that efficiently delivers the intelligence assessment.

In the AFIT simulation dissemination occurs between the CAOC and the ground forces conducting the mission. It can also take place directly between the sensors and

ground forces. Both the method of dissemination and the path over which dissemination occurs can significantly change layered sensing performance, so numerical experiments characterizing dissemination are critically important to the AFIT effort. Dissemination is not just transmission; it is transmission that effectively and efficiently couples intelligence assessments to the force command structure that needs them.

2.7 Arena Discrete Event Simulations

The Arena simulation software environment produced by Rockwell Software Inc. was the tool used to build the discrete event simulation. The literature review included searches for training material in order to maximize efficient use of the Arena software. Although perhaps not as interesting as some of the other items described in this chapter, two sources of Arena knowledge were just as pivotal for project success as any other piece of literature used during the research.

The first Arena source was the Arena Basic User's Guide written by Rockwell. It provided the elementary descriptions of Arena components, programming philosophy, and syntax necessary to get the simulation effort started. (8)

As the simulation quickly grew in complexity the SMARTs library (part of the robust help function in the Arena software package) became the most important source for Arena knowledge. The library contained a large number of SMART files that were samples of Arena code simulating processes of interest for capturing discrete events. These smart file examples helped the researchers build some of the processes included in the layered sensing simulation. (9)

3. Methodology

3.1 Overview

This chapter describes the methodology used to look for a correlation between the measurement of interoperability and MOEs that characterize system performance. The description begins by discussing steps taken to scope the problem and prepare the simulation framework. Once this is complete, the experimental construct is discussed. Next, the calculation of the interoperability measurement technique is explained. Execution of the technique is linked to the discrete event simulation; each experiment must have a measure of interoperability accompanied by a set of MOEs so that comparisons can be made with the baseline architecture. As such, the simulation approach is addressed next. The chapter culminates with a discussion of how the two parts of the experimental process – interoperability measurement and MOE evaluation – are linked to look for the correlation. Lastly, sample test plans are presented to facilitate the presentation of results in Chapter 4.

3.2 Scoping and Preparation

The layered sensing architecture built by AFRL/RY describes a system of systems used to perform ISR missions. The collection of systems not only includes platforms and sensors, but functions residing in the CAOC and the forces requiring ISR support, as well. The complex nature of layered sensing made system familiarization an early goal. Familiarization also facilitated the scoping effort. Most of the system information came from the aforementioned AFRL white paper, discussions with the research sponsor,

various briefings and documents, and presentations given during an AFRL industry day held in December 2008.

Figure 6 shows the scoping process that moved the research effort from AFRL white paper to experimental construct. There were three separate paths of study. The first path identified a scenario of interest which fostered development of the discrete event simulation. The second path identified important interoperability characters. The third and final path led to selection of the MOEs. Blocks with blue text denote scoping steps taken by AFIT. Blocks with green text denote AFRL provided information.

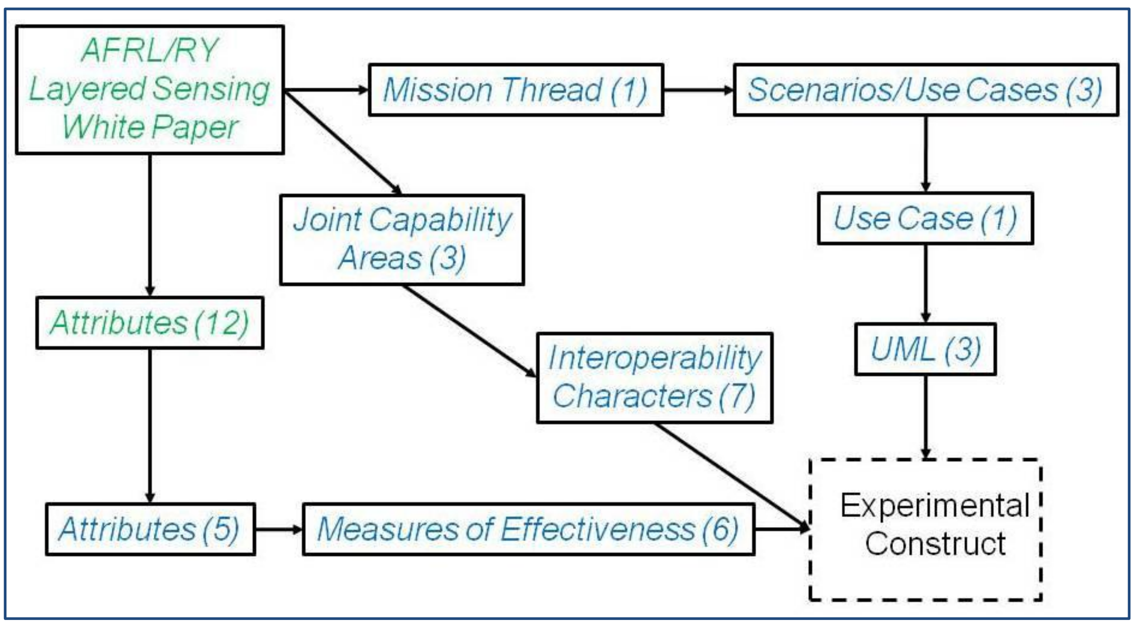


Figure 6. The Scoping Process

Discussions with the sponsor quickly focused interest on an urban mission thread. That focus drove the selection of platforms and sensors discussed in Chapter 1, all of which were used for both the interoperability measurement and the MOE evaluation produced by the simulation. Both the simulation and the interoperability measurement

technique can be executed for other platforms or sensors, but those in Table 1 (Chapter 1) best captured the interests of the sponsor and the researchers.

Once the mission thread and accompanying platforms and systems were selected, the next step was learning how layered sensing operates. The tool of choice was use case development done in conjunction with the sponsor. Three use cases were built to describe three different layered sensing applications (see Table 5 and Appendix 1). Of these three, UC 2 was selected for study because it presented interesting challenges for any layered sensing architecture, and so constituted a useful benchmark for comparison.

Table 5. Use Case Descriptions

Use Case	Condition Under Test
UC 1: Maintain surveillance over a fixed point	Ability to identify and analyze patterns of activity. Goal is evaluating ability to successfully recognize event tip-offs
UC 2: Track friendly force movements and reactions	Ability to react to changes in operational conditions, especially convoy re-routing in response to enemy action. Goal is evaluating ability to maintain platform and sensor support to ground forces
UC 3: Survey fixed point for forensic analysis	Ability to route information to where it is needed. Goal is evaluating CAOC ability to identify, store, retrieve, analyze, and disseminate relevant intelligence

Selection of a specific scenario (UC 2) was the first step needed for construction of the discrete event simulation. This was followed by creating static and dynamic representations of the layered sensing systems. The first of these representations was an object diagram (see Figure 7). Although static, the object diagram showed what objects needed to interact in the simulation in order to accomplish the scenario mission. Insight was also gained for required multiplicities and the interactions between specific objects.

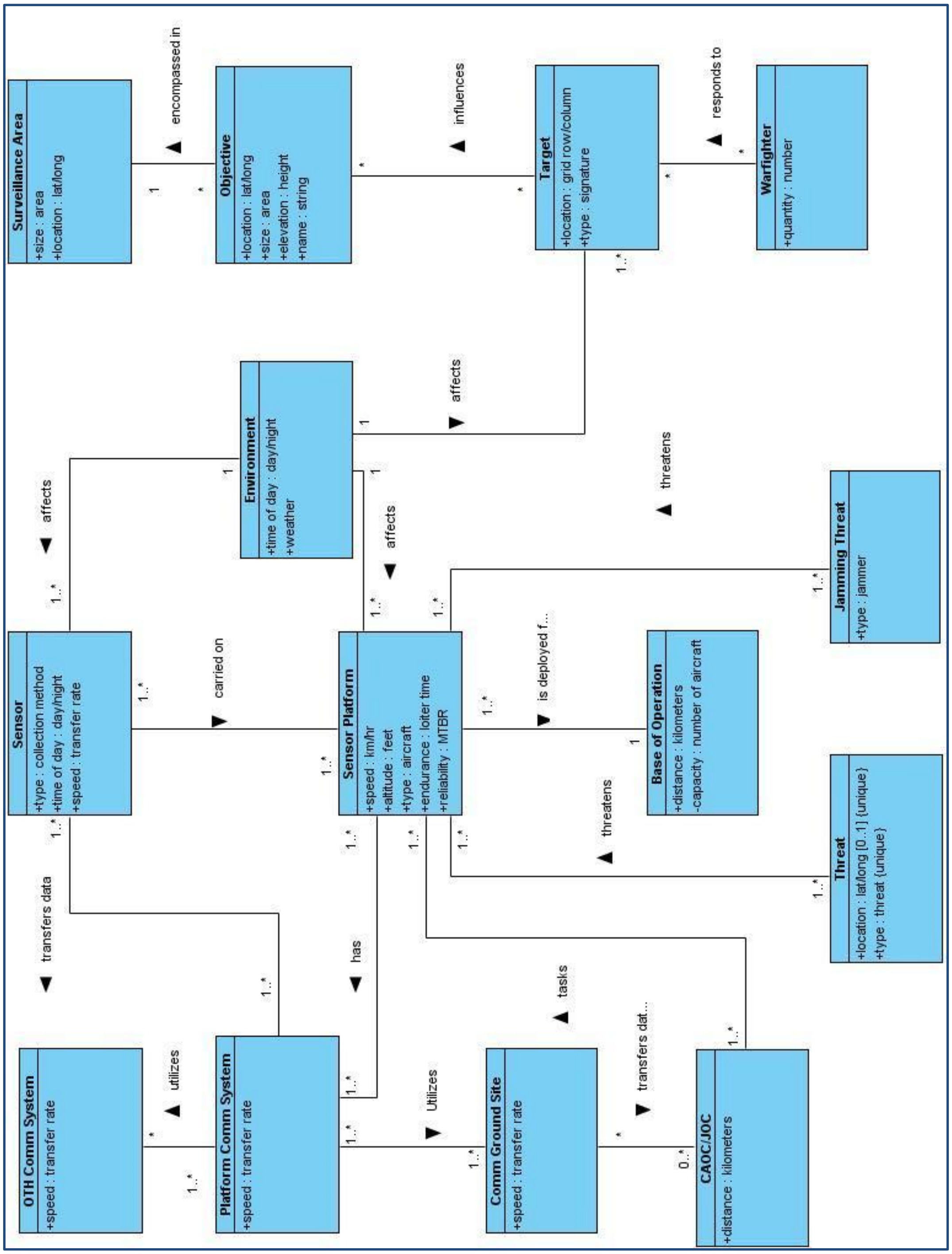


Figure 7. Layered Sensing Object Diagram

The next model built was a sequence diagram (see Figure 8). This diagram was the first dynamic view of the system and provided insight into what operations are carried out by the different objects and the order (in time) in which they must occur. Establishing the sequence of actions drove construction of the discrete event simulation and also assisted in MOE selection.

The last representation built by the researchers was the activity model (see Figure 9). This model explored both the logical entities in layered sensing and the data that is used or transferred by each entity. The activity model also helped directly transfer characteristics captured by all three models into the Arena discrete event simulation software environment.

The use of Unified Modeling Language (UML) tools during the early stages of research solidified the perception of layered sensing, its system components, and its mission applications. The UML models were key enablers for crafting a robust discrete event simulation that met the needs of AFRL and AFIT.

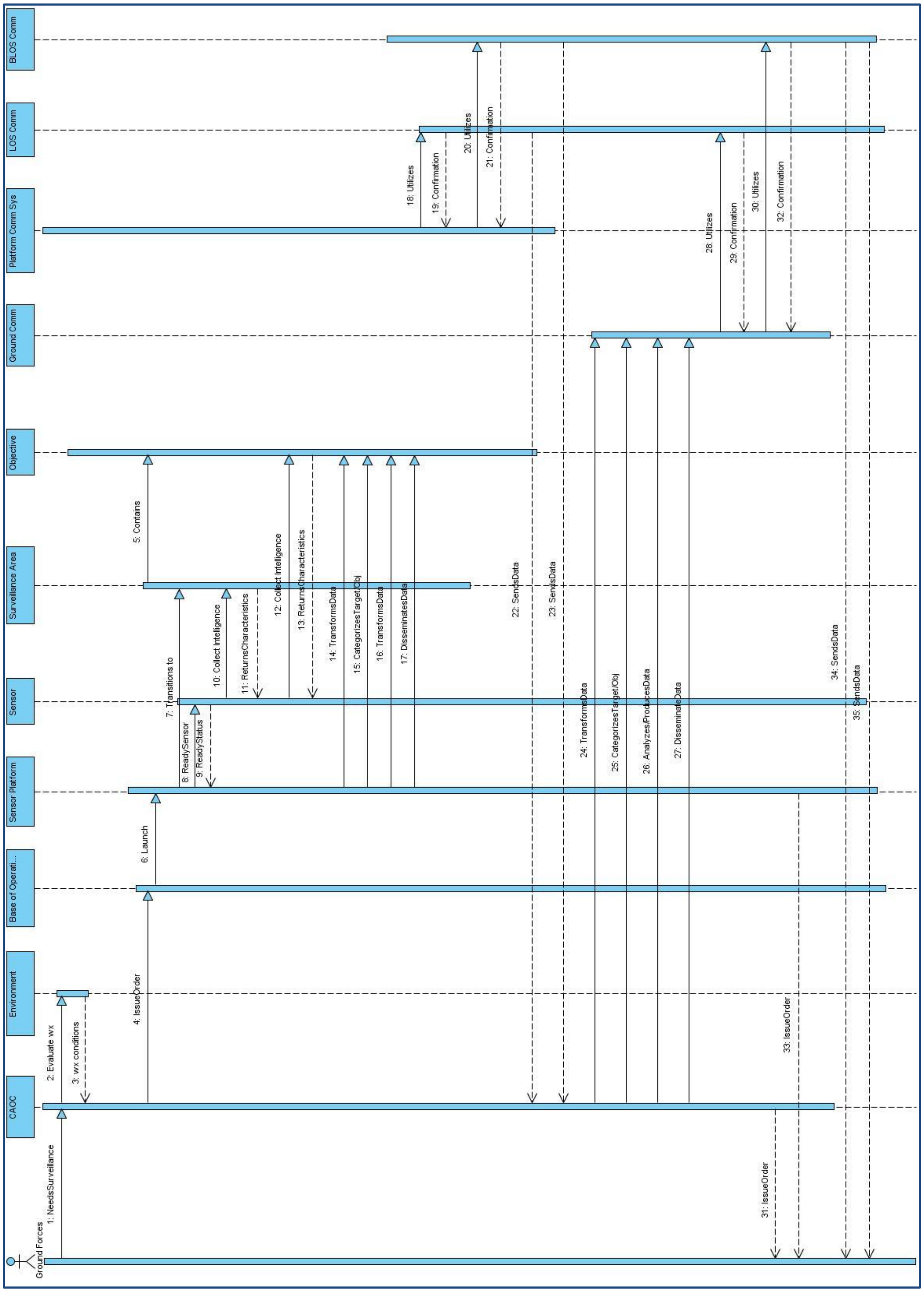


Figure 8. Layered Sensing Sequence Diagram

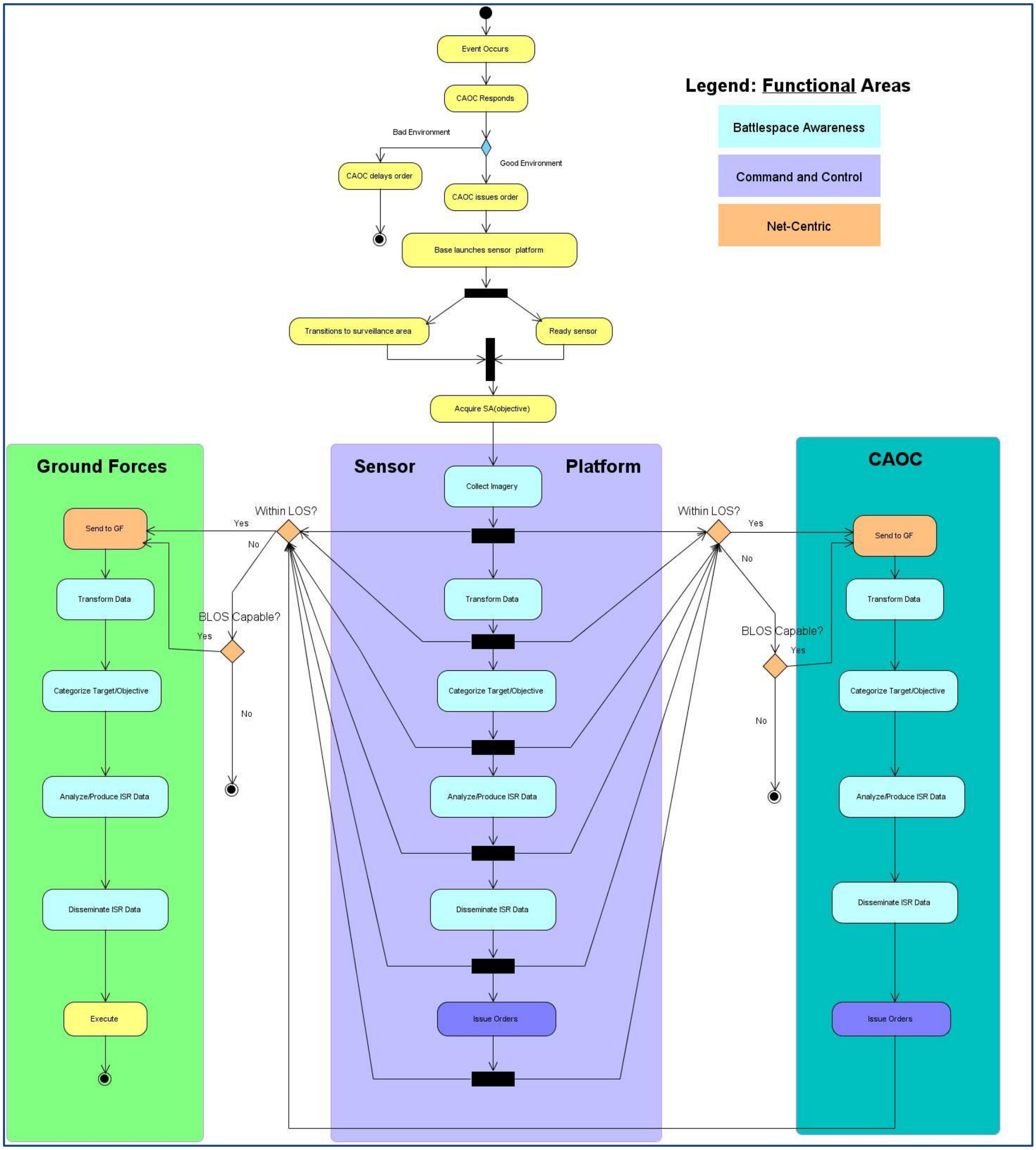


Figure 9. Layered Sensing Activity Model

3.3 Experimental Construct

Ford identified a process, depicted in Figure 10, for measuring interoperability. Although Ford's application was interoperability analysis, the current researchers use this process as a construct for both components of the experimental procedure: measuring interoperability and calculating MOEs. In essence, Figure 10 serves as a map that guides the interested reader through the experimental setup.

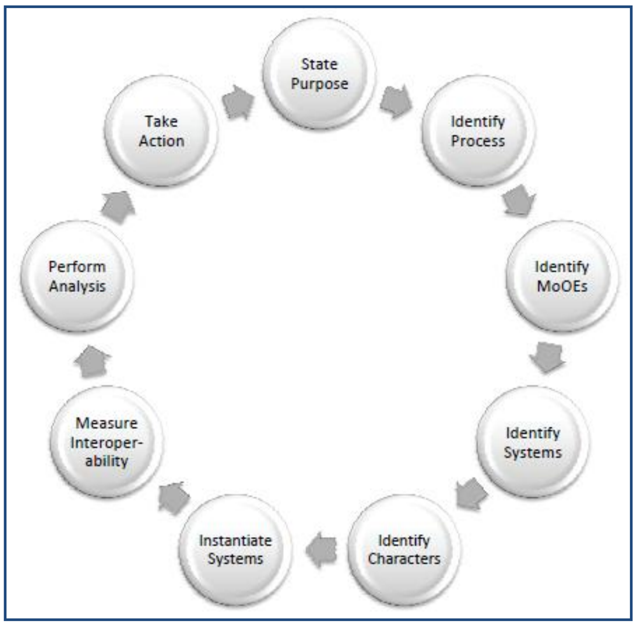


Figure 10. Ford's Interoperability Measurement Process (6:28)

By using the process shown in Figure 10, the need for and role played by each stage becomes clear. Following Ford's process reinforces sound systems engineering principles, such as maintaining traceability to validated documents (e.g. requirements). The process diagrammed in Figure 10 is executed by the experimental construct shown in Figure 11. This is the same construct alluded to in Figure 6, which showed the scoping process followed during research.

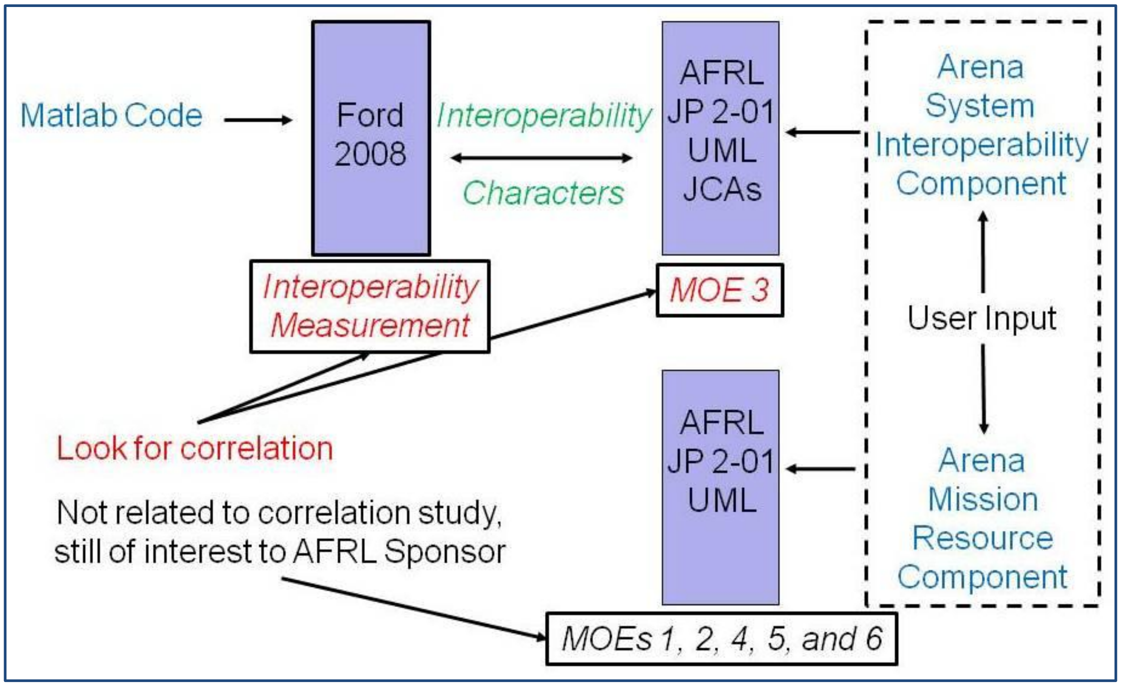


Figure 11. The Experimental Construct

There are three components in the experimental construct. The first component captures the interoperability measurement by executing Ford's technique. This component was built with Matlab. The second component calculates MOE 3 and is based on the AFRL white paper, JP 2-01, UML representations, and JCA-provided interoperability characters. This component, called the system interoperability component, was built with Arena. It is linked to the interoperability measurement component by a common set of interoperability characters. Recall that one of the primary research goals is to look for a correlation between the interoperability measurement and the MOEs related to interoperability.

During the course of research, it was determined that only one of the six established MOEs was directly linked to interoperability (MOE 3). Although the other

MOEs are important to AFRL/RY, they are not part of the correlation study. This is why the system interoperability component only captures one MOE.

The other MOEs are captured by the third experimental component which is called the mission resource component. Like the system interoperability component, this part of the experiment is based on the AFRL white paper, JP 2-01, and UML representations of the layered sensing system. It is executed with Arena.

The two Arena components are linked by a common user interface (UI), shown in Figure 12. This UI is an Excel spreadsheet in which the user inputs layered sensing system features that describe platforms, sensors, and other elements of the simulation. The Arena software reads these inputs as variables and uses them to initialize the discrete event simulation.

Although linked by a common user input, the two Arena simulation components do not use the same process flow. Figures 13 and 14 display the processes executed by the simulation. Figure 13 shows the process that captures MOE 3, which is measured with units of time. This process encapsulates the ISR mission as described in JP 2-01. Figure 14 shows the process that captures MOEs 1, 2, 4, 5, and 6. These MOEs are related to reliability, coverage, mission failures, and other performance metrics. These MOEs are important for comparing different layered sensing architectures, but are not directly related to interoperability.

User Interface for Input into ARENA simulation

	account for day/night	start daylight [hrs]	end daylight [hrs]
day/night visibility	1	5	19
	v_day_night(1,1)	v_day_night(1,2)	v_day_night(1,3)

	probability of bad weather	random event time
weather influence	0.10	1
	v_weather	v_random_event

systems	System Number	1	2	3	4	5	v_Aircraft_Type
	System Name	"LAIR"	"ARGUS-IS"	"GOTCHA"	"NITESTARE"	"generic"	v_System_Name(x,1)
	total #	4	2	2	4	3	v_Number_of_Systems(x,1)
	# at HB	4	1	1	3	2	v_Number_of_Systems(x,2)
aircraft	speed [km/h]	450.0	260.0	480.0	450.0	800.0	v_Speed(x,1)
	mission time [hrs]	7.0	20.0	6.0	7.0	10.0	v_Loiter_Time(x,1)
sensors	EO sensor	1	1	0	0	1	v_Sensor_Type(x,1)
	IR sensor	0	0	0	1	1	v_Sensor_Type(x,2)
	SAR sensor	0	0	1	0	1	v_Sensor_Type(x,3)
	sensor radius [km]	4.00	3.00	20.00	5.00	10.00	v_Sensor_Footprint(x,1)
communications	SATCOM	0	0	0	0	1	v_SATCOM_Capable(x,1)
	Voice Comms to Ground Unit	1	1	1	1	1	v_VOICE_Capable(x,1)
reliability	aircraft	0.95	0.85	0.95	0.95	0.90	v_Reliability(x,1)
	sensor	0.90	0.85	0.80	0.85	0.80	v_Reliability(x,2)
	comms	0.95	0.95	0.95	0.95	0.95	v_Reliability(x,3)
night operations	night capable (a/c & sensor)	0	0	1	1	1	v_Night_Ops(x,1)

	rows	columns	size [km]	coverage limit
gridsize	50	50	1.00	2
	v_gridsize_rows	v_gridsize_columns	v_Keypad_Size	v_Aircraft_Limit

	homebase --> AOR entry point [km]	CAOC --> AOR [km]
distances	50.0	125.0
	v_Distances(1,1)	v_Distances(2,1)

Figure 12. Discrete Event Simulation User Interface

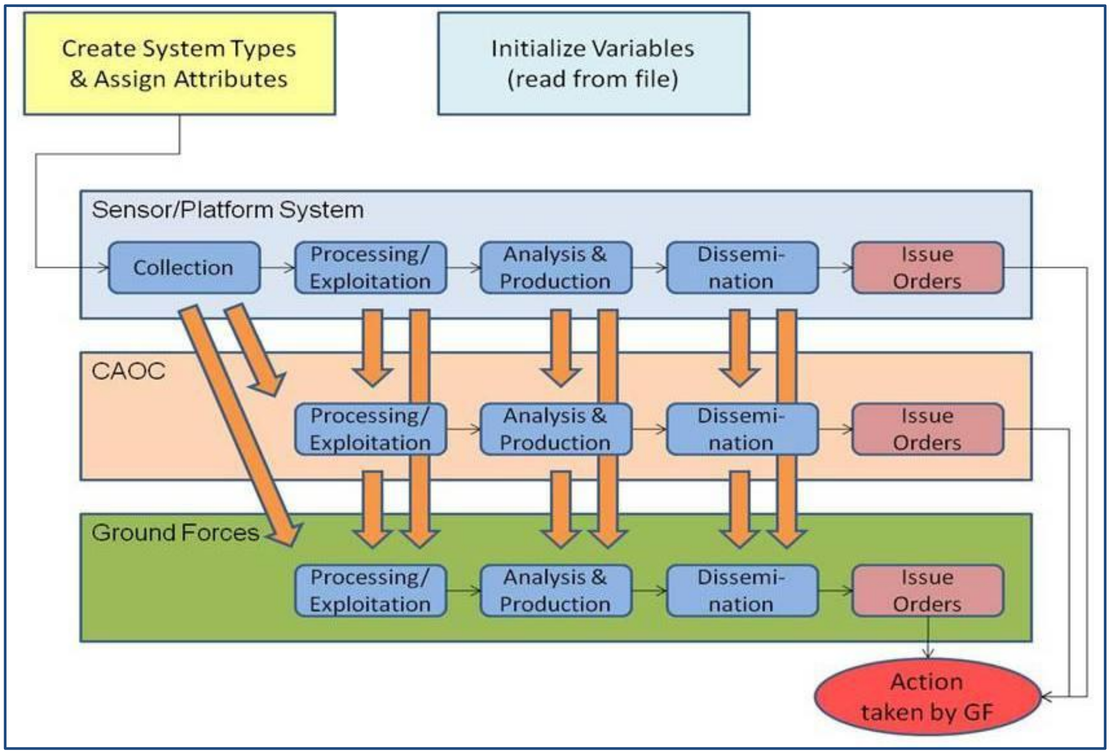


Figure 13. Simulation Process Flow for the System Interoperability Component

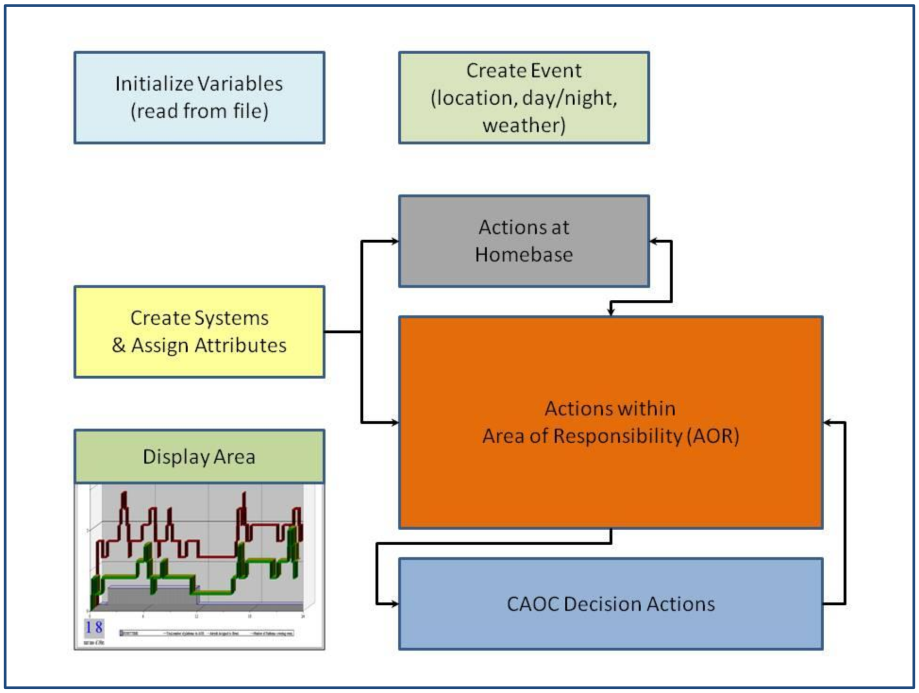


Figure 14. Simulation Process Flow for the Mission Resource Component

3.4 Measuring Interoperability

Ford's process starts by stating a purpose. For the current research, the general purpose (or perhaps interest) has at least two elements linked to vetted DoD interoperability discussions: measure system-to-system compatibility, and determine ISR product distribution bottlenecks (4:III-7). As the focus narrows to layered sensing, the specific purpose becomes generating quantitative comparisons of different layered sensing architectures, with an emphasis on interoperability.

The next step is identifying a specific process. Starting once again with a general perspective, the natural candidate is outlined in JP 2-01, "Joint and National Intelligence Support for Military Operations." Moving towards a specific process gives that outlined in UC 2. The two processes complement each other and when mated together provide the specific ISR process mimicked by the simulation.

MOE selection is next. The MOEs that are selected to evaluate system performance must be linked to the attributes drawn from the AFRL white paper that characterized layered sensing. The use case chosen for emulation should also influence MOE selection. Recall that the MOEs are listed in Table 3. MOE identification is one of three critical links between the experimental components. The other two links are discussed next.

System identification is driven by an understanding of the layered sensing architecture. For this research, there are three broad categories of systems: platforms and sensors, the CAOC, and the ground forces conducting the mission of interest. The ground force characteristics (e.g. mission time) are set to ensure the consistency of comparisons made between different architectures. Features for the platforms, sensors,

and the CAOC can be changed from one experimental trial to the next. Feature selection is driven by the UI shown in Figure 12.

Interoperability character selection is the next step. Successful selection requires a good understanding of the current layered sensing architecture, knowledge of potential future changes to the system, and access to DoD-validated descriptions of interoperability. Joint Capability Areas (JCAs) and Joint Integrating Concepts (JICs) provided the requisite insight into ISR capabilities required by US forces. The Battlespace Awareness, Command and Control, and Net-centric JCAs were picked as the final sources for the interoperability characters used during experimentation (specific character definitions are in Appendix A2). Recall that Table 4 shows the characters that were selected and the specific source from which they came. Character changes represent potential new capabilities and are sometimes synonymous with changes in architecture. The interoperability characters used for experimentation are directional and the states are all absence/presence states. (6:42-45) Understanding this notion might be enhanced by applying one of the interoperability views (IV) introduced by Ford (6:65-70) as possible additions to DOD Architectural Framework (DoDAF). In particular, the interoperability graph (IV-2) seems appropriate for deriving a better understanding of the involved systems and their interoperations as an intermediate step towards the following instantiation of systems. Figure 15 is a schematic instantiation of an IV-2 for the layered sensing architecture at hand.

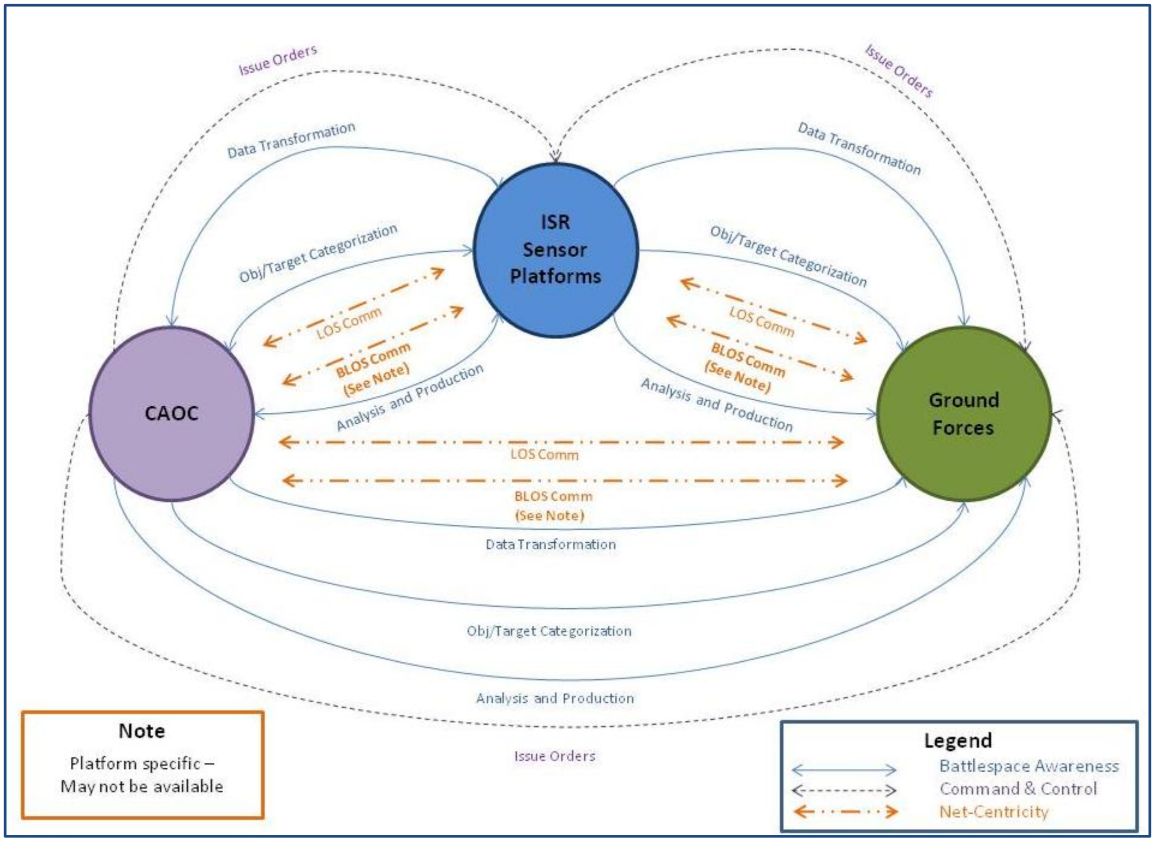


Figure 15. Interoperability Graph (IV-2)

The next step is instantiating the systems used to produce the interoperability measurement, and essentially combines the systems and characters with their state values. Table 6 shows an example of the instantiation process. In this case, the baseline architecture for layered sensing is displayed. The interoperability characters run vertically on the left in the table, and the systems run horizontally along the top. The table is split in the middle, "in order to accommodate the directionality of interoperability characters" (6:43). The left half shows the "transmit/can actively do" states while the right half shows the "receive/can understand or work with" states. The bolded interoperability characters are the elements under test during the experiments. For the

purpose of this work all states were defined as either being "absent" (value 0) or "present" (value 1), thereby allowing the use of a specific interoperability measurement method on system similarity (Equation 1).

The measure of interoperability (*I*) can be calculated once the systems have been instantiated (6:50). The appropriate calculation for Sim_{Bin} (binary system similarity) is given as

$$\boldsymbol{I} = \mathbf{Sim_{Bin}} = \left(\frac{\mathbf{1}}{\mathbf{n}}\right)\sum_{\mathbf{i=1}}^{\mathbf{n}}(\,\boldsymbol{\sigma}'(\mathbf{i}) \wedge \boldsymbol{\sigma}''(\mathbf{i})\,). \quad (1)$$

The resulting matrix values resemble a normalized value (over n characters) for the similarity between two systems on each character (expressed by the Boolean AND operator ∧) out of the system instantiating sequences σ' and σ''. Table 7 shows the results of the measurement for the system instantiation given in Table 6. The transmit character direction for the various systems is shown on the vertical axis with the receive character direction shown on the horizontal axis. The individual interoperability measures are shown as fractions to allow for easy reading of the number of similarities out of the overall number of characters. By definition, a system is not to be considered interoperable with itself (6:54), therefore the main diagonal values are set to zero. For this project it can be assumed that there is no interaction between the individual sensor systems. Although the calculation provides values for sensor to sensor interoperability they are to be considered meaningless for the remainder of this project.

The interoperability measurement calculations were generated by using a Matlab routine that implemented Equation 1. The code that executes the routine is found in Appendix A3.

Table 6. System Instantiation for all Interoperability Characters

JCA Definition Number and Description		transmit / can actively do							receive / can understand or work with						
		BLUE SYSTEMS					BLUE PLAYERS		BLUE SYSTEMS					BLUE PLAYERS	
		LAIR	ARGUS-IS	GOTCHA	NITE STARE	generic	CAOC	GF	LAIR	ARGUS-IS	GOTCHA	NITE STARE	generic	CAOC	GF
2.	Battlespace Awareness	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2.1	Intelligence, Surveillance and Reconnaissance	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2.1.2	Collection	1	1	1	1	1	0	0	1	1	1	1	1	1	1
2.1.2.3	Imagery Collection	1	1	1	1	1	0	0	1	1	1	1	1	1	1
2.1.2.3.1	Electro-Optical Imagery Collection	1	1	0	1	1	0	0	1	1	0	1	1	1	1
2.1.2.3.1.1	Panchromatic Collection	1	1	0	0	1	0	0	1	1	0	0	1	1	1
2.1.2.3.1.2	Infrared Collection	0	0	0	1	1	0	0	0	0	0	1	1	1	1
2.1.2.3.2	RADAR Imagery Collection	0	0	1	0	1	0	0	0	0	1	0	1	0	0
2.1.3	Processing / Exploitation	1	1	1	1	1	1	1	0	0	0	0	0	1	1
2.1.3.1	Data Transformation	1	1	1	1	1	1	0	0	0	0	0	0	1	1
2.1.3.2	Objective / Target Categorization	1	1	1	1	1	1	1	0	0	0	0	0	1	1
2.1.4	Analysis and Production	1	0	1	1	0	1	1	0	0	0	0	0	1	1
2.1.5	Intelligence, Surveillance and Reconnaissance Dissemination	1	0	1	1	0	1	1	0	0	0	0	0	1	1
5.	Command and Control	1	0	1	1	0	1	1	1	1	1	1	1	0	1
5.5	Direct	1	0	1	1	0	1	1	1	1	1	1	1	0	1
5.5.2	Task	1	0	1	1	0	1	1	1	1	1	1	1	0	1
5.5.2.1	Synchronize Operations	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.5.2.2	Issue Plans	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.5.2.3	Issue Orders	1	0	1	1	0	1	1	1	1	1	1	1	0	1
6.	Net-Centric	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6.1	Information Transport (IT)	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6.1.2	Wireless Transmission	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6.1.2.1	Line of Sight	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6.1.2.2	Beyond Line of Sight	0	0	0	0	1	1	0	0	0	0	0	1	1	0

At this point in the experiment, the interoperability measurements have been made. The specific example in this section shows the baseline measurement (how layered sensing exists today), and serves as the basis for comparison with all of the experimental trials that change various characters. Completing Ford's process requires analysis and actions (in this case actions are poised as recommendations). These two steps are dealt with in Chapters 4 and 5 and will not be discussed here.

Table 7. Layered Sensing Baseline Architecture Interoperability Measurement

		LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
BASELINE	LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
	ARGUS-IS	5/12	0	1/3	3/8	5/12	**13/24**	**13/24**
	GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
	NITESTARE	13/24	13/24	1/2	0	7/12	**5/8**	**19/24**
	GENERIC	5/12	5/12	3/8	5/12	0	**5/8**	**7/12**
	CAOC	**5/12**	**5/12**	**5/12**	**5/12**	**11/24**	**0**	**5/8**
	GF	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**0**

3.5 Calculating Measures of Effectiveness

The process that generates interoperability measurements also guides construction of the discrete event simulation. The starting point is certainly the same: vetted DoD joint doctrine and policy. The same guidance that shaped general purpose and process selection for Ford's technique also applies to the simulation: JCAs, JICs, and JP 2-01. For the specific focus, attention centers on simulating UC 2 with the current layered sensing architecture. The MOEs calculated by this specific UC 2 simulation constitute the baseline to which experimental trials will be compared. Each numerical experiment represents a change in the state of one or more interoperability characters and calculates new MOE values.

Selecting MOEs for evaluating performance is critical to the experimental process. As the simulation was built and tested, it became obvious that only one of the MOEs identified during the execution of Ford's technique for measuring interoperability graded performance in a way clearly linked to interoperability (Table 3, MOE 3). This observation led to breaking the simulation into two parts: a part that calculates values for MOEs not related to interoperability (but still desired by the sponsor) called the mission resource component and a part that calculates the value of the one MOE that is related to interoperability called the system interoperability component.

Just as with the execution of Ford's technique, systems and interoperability characters must be indentified before and during construction of the simulation. The systems listed in Table 1 are in the discrete event simulation, and are characterized by the UI spreadsheet shown in Figure 12. The bolded interoperability characters shown in Table 6 are included in the simulation.

There was no clear point where preparation stopped and simulation construction began: for a significant period of time both steps were in progress. Building the model became more than just crafting an experimental tool. As much insight into interoperability was gained while the model was built as was secured during numerical experimentation. Interested readers will find a detailed treatment of the Arena simulation code in Appendix A5.

The simulation must capture values for MOEs, especially the MOE related to interoperability. However, MOE values could not be correlated to Ford's interoperability measurements unless interoperability characters are also addressed. The interoperability characters are represented by decision nodes in the simulation component that calculates

the MOE related to interoperability. A given character presence state (a “1” in Table 6) corresponds to a “yes” in an Arena simulation decision node. A decision node “yes” opens a new path that a packet of data (in the simulation) can follow as it travels from a sensor on a platform to the ground forces. A “no” in a decision node means the data packet must reach the ground forces by a different path. So decision nodes are not only important because they provide the mechanism that allows for character linkage between Ford’s technique and the simulation, they also drive one of two simulation outputs: number of paths that data can follow through the ISR process in order to get from sensor to ground forces. For the duration of this report, these paths are called “process paths.”

The simulation is demonstrated with the baseline performance output. Recall that baseline means layered sensing system characterization as the architecture is currently defined. Figure 16 shows the time it takes for data to travel from the sensor/platform to the ground forces. Recall that there are five sets of histograms shown in Figure 16 because the simulation contains five different sensor/platform systems. Three different results are graphed for each named system. The simulation ran 250 times to characterize the baseline (all experimental trials were executed either 250 or 500 times), so the average time it takes for data gathered by a system to travel to the ground forces is graphed. This graph also has bars denoting the 95% confidence interval. The other two graphed outputs are maximum average and minimum average times a data packet from a given system needed to traverse the available process paths to the ground forces.

The results from six experimental runs will be presented in Chapter 4. Although the display format remains constant, these time plots are different than that shown for the baseline performance because they show a time difference (vice a time of completion).

The difference is (baseline – experiment). So a plot with a positive time value implies better performance for the experimental interoperability character state change. A negative time value implies that the baseline performed better.

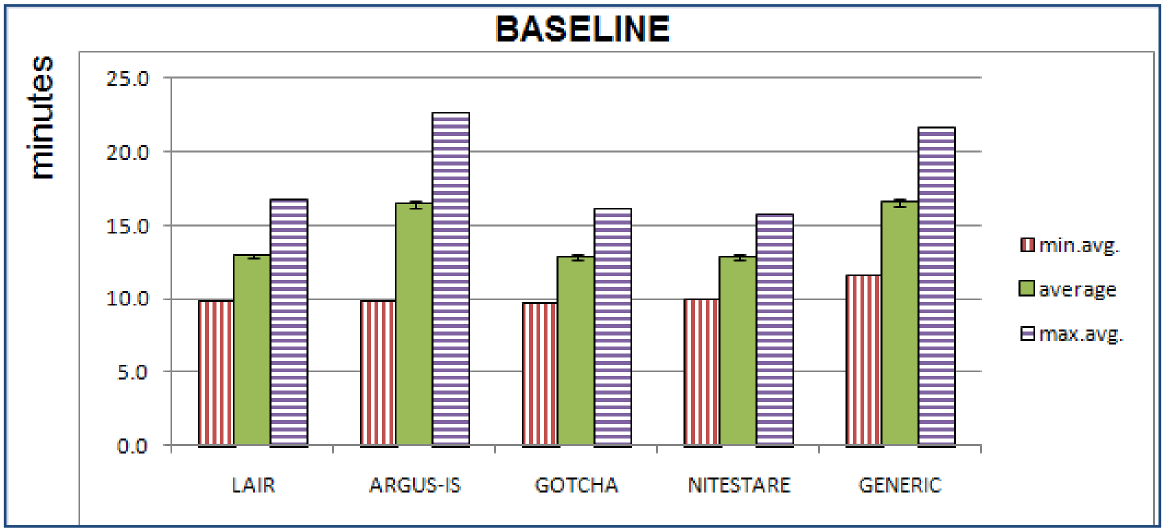


Figure 16. Baseline Performance -- Time for Data to Travel from Sensor/Platform to Ground Forces

Figure 17 records the number of process paths that data from each system can take to reach the ground forces for the baseline layered sensing architecture. The corresponding plots for the experimental trials shown in Chapter 4 graph two numbers for each system: number of process paths before and after the interoperability character state was changed (baseline path number and experimental path number). Figure 16 and Figure 17 are the outputs from the simulation component that captures the MOE related to interoperability. Figure 16, time for data to travel from sensor to ground forces, is a plot of the MOE. The mission resource simulation component produces plots with a different format than that shown in Figure 16 and Figure 17, but the presentations are straight-forward and do not require any preparatory discussion outside of Chapter 4.

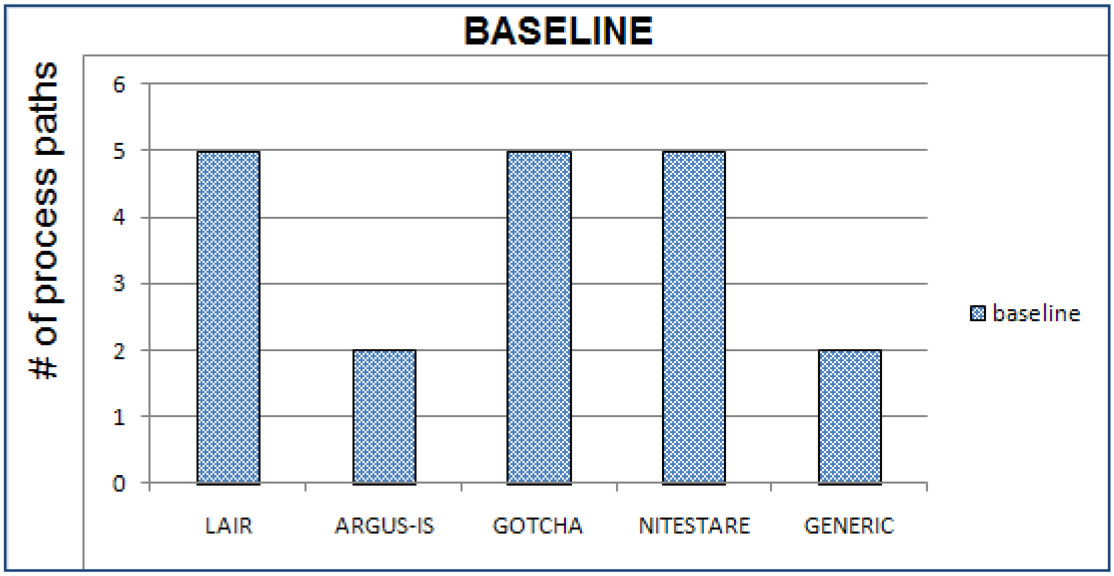


Figure 17. Baseline Performance -- Number of Process Paths Data Can Take between Sensor and Ground Forces

3.6 Linking Interoperability Measurements and Measures of Effectiveness

One of the research goals for this project was testing for correlation between Ford's interoperability measurements and discrete event simulation captured-MOE values. Pursuit of this goal requires a balancing act between the execution of Ford's technique and the simulation trials. The two experimental components must have parallel constructs so that meaningful comparisons can be made. However, input used for one component cannot improperly influence the other component's performance.

There are three elements in place to prevent improper influence: interoperability characters, character state values, and MOEs. The selection of interoperability characters serves as the focal point for balance. The initial list of potential characters came from DoD doctrine and policy. As UC 2 began to unfold in the Arena simulation the researchers gained insight into what characters were relevant. Reality – or at least reality

as it is represented by the simulation – drove character selection. The final list of characters that matured from the simulation was imported for use in Ford's interoperability measurement technique.

Once the characters were set, an initial character state configuration was required. The initial state values (0s or 1s) were driven by the current layered sensing architecture. An experiment constitutes a potential future capability change for the layered sensing system of systems. This potential change in capability is represented by a change in state value for at least one interoperability character. The change of state links a specific interoperability measurement to a specific MOE value.

The MOEs are linked to and driven by the layered sensing attributes described by AFRL; the MOEs are the performance yardstick for all components of the simulation. An increase in interoperability measurement is not considered an architecture improvement unless there is a corresponding improvement in MOE value. The AFIT researchers think the way that characters, state values, and MOEs were determined, used, and calculated both ensure the proper linkage between the experimental components and limit any undue influence between interoperability measurement and MOE calculation.

There is one final note regarding MOEs. Calculating a MOE for specific systems stretches the definition of MOE in an undesirable direction: towards that of a MOP. The researchers realize this, but the need for MOEs and MOPs came about during experimentation and will be discussed in detail in Chapter 4.

3.7 Experimental Test Plans

The number of potential interoperability character state changes allows for a large number of experiments, even when interest is constrained to interoperability. This rich experimental environment was the design intent: more experiments provide more insight into different layered sensing architectures. Including a complete listing of potential experiments would be cumbersome, so two test plans are provided for the experiments discussed in Chapter 4 and they stand as surrogate examples for other possible executions of the methodology. The two plans test both parts of the simulation.

Table 8 shows the test plan for exploring correlation between interoperability measurements and MOE calculations. It captures a complete set of experiments needed to explore the core research goal.

Table 8. System Interoperability Test Plan

Trial Number	Interoperability Character under Test	Rationale
IE 1	2.1.2.3.1.2 Infrared Collection	Add IR sensor to Argus system … quantify interoperability impact, take advantage of Argus loiter time, provide day/night coverage
IE 2	6.1.2.2 Beyond Line of Sight (BLOS)	Add BLOS capability to ground forces … quantify interoperability impact when CAOC talks directly to ground force element
IE 3	6.1.2.2 BLOS	Add BLOS capability to the Argus system … quantify interoperability impact when CAOC and platform no longer have to be within line-of-sight (LOS)

IE 4	6.1.2.1 LOS	Move CAOC within LOS of the AOR (< 175 km) … does not directly change any character, but impacts LOS communication for layered sensing system
IE 5	2.1.2.3.1.2 Infrared Collection 6.1.2.2 BLOS	Add two interoperability characters for the Argus system … quantify interoperability from mixed characters state impacts
IE 6	2.1.4 Analysis and Production 2.1.5 Intelligence, Surveillance and Reconnaissance Dissemination	Add two interoperability characters for the generic system… quantify impact of significant interoperability improvement

Table 9 shows a sampling of simulation experiments that characterize different layered sensing architectures. Although not linked to interoperability measurements, these MOE comparisons can support future acquisition decisions affecting layered sensing.

Table 9. Mission Resource Experimental Test Plan

Trial Number	**Measure of Effectiveness under Test**	**Action**
ME 1	Potentially MOEs 1, 2, 4, 5, and 6	Add IR sensor to Argus
ME 2	Potentially MOEs 1, 2, 4, 5, and 6	Lower aircraft reliability for generic platform
ME 3	Potentially MOEs 1, 2, 4, 5, and 6	Change from summer to winter, decrease in amount of daylight
ME 4	Potentially MOEs 1, 2, 4, 5, and 6	Decrease number of platforms available for tasking

4. Analysis and Results

4.1 Overview

This chapter contains the results from all components of the experimental construct. The possible correlation between interoperability measurement and MOE 3 is explored first. The next section describes the concept of an ISR process path and its potential impact on interoperability. Next, the difference between MOE and MOP as it relates to this research effort is addressed. The chapter concludes with the mission resource MOE experiments.

4.2 Interoperability Measurements and Measures of Effectiveness

This section is organized by system interoperability experiment (reference Table 8). First, the interoperability measurement for the baseline configuration of layered sensing is shown again in Table 10 so that the reader does not need to search for the earlier reference.

Table 10. Baseline Interoperability Measurement

	LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
ARGUS-IS	5/12	0	1/3	3/8	5/12	**13/24**	**13/24**
GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
NITESTARE	13/24	13/24	1/2	0	7/12	**5/8**	**19/24**
GENERIC	5/12	5/12	3/8	5/12	0	**5/8**	**7/12**
CAOC	**5/12**	**5/12**	**5/12**	**5/12**	**11/24**	**0**	**5/8**
GF	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**0**

The discrete event simulation produced six sets of experimental results for system interoperability testing. Four sets are discussed in this section. Experiments IE 3 and IE 5 (see Table 8) are not covered because they do not add insight beyond that provided by the four experiments that are presented. For a given experiment, one table and one or two figures may be shown for discussion. The table shows both the interoperability measurement and changes from the baseline measurement (in parentheses). The figures either show average (with 95% confidence intervals), minimum average, and maximum average MOE values or the number of process paths. Analytical comments are provided for each experiment. Figures are only included if they are necessary for the discussion.

The primary goal for these experiments was to look for a statistical correlation between interoperability measurement and MOE 3. The results show that as far as the simulated scenario is concerned, no correlation exists. Despite this finding, several other useful observations were made and will be discussed in this chapter and Chapter 5.

Experiment IE 1: Argus System Receives IR Capability

Analytical Comments:

In this experiment, an interoperability character state was changed so that the Argus system would have a new IR sensor. Table 11 shows that the interoperability measurement did increase, albeit slightly. This result means that according to Ford's technique the layered sensing architecture in IE 1 is more interoperable than the architecture in the baseline. One can consider Argus more common (shared capability) with Nitestare and the Generic system. However, the simulation results for MOE 3 shown in Figure 18 show no significant improvement in effectiveness. This is to be

expected, since the interoperability character selected for experimentation did not increase the number of ISR process paths present in the architecture (see Figure 19).

This experiment accomplishes two tasks. First, and most importantly, it shows that a change in interoperability measurement is not always accompanied by a significant change in mission effectiveness. Second, it helps validate simulation performance. The values for MOE 3 should not change significantly unless the number of process paths changes, so IE 1 shows that the simulation is performing as designed.

Table 11. Experiment IE 1 Interoperability Measurement

	LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
ARGUS-IS	5/12	0	1/3	5/12 (1/24)	11/24 (1/24)	**7/12 (1/24)**	**7/12 (1/24)**
GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
NITESTARE	13/24	7/12 (1/24)	1/2	0	7/12	**5/8**	**19/24**
GENERIC	5/12	11/24 (1/24)	3/8	5/12	0	**5/8**	**7/12**
CAOC	**5/12**	**5/12**	**5/12**	**5/12**	**11/24**	**0**	**5/8**
GF	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**0**

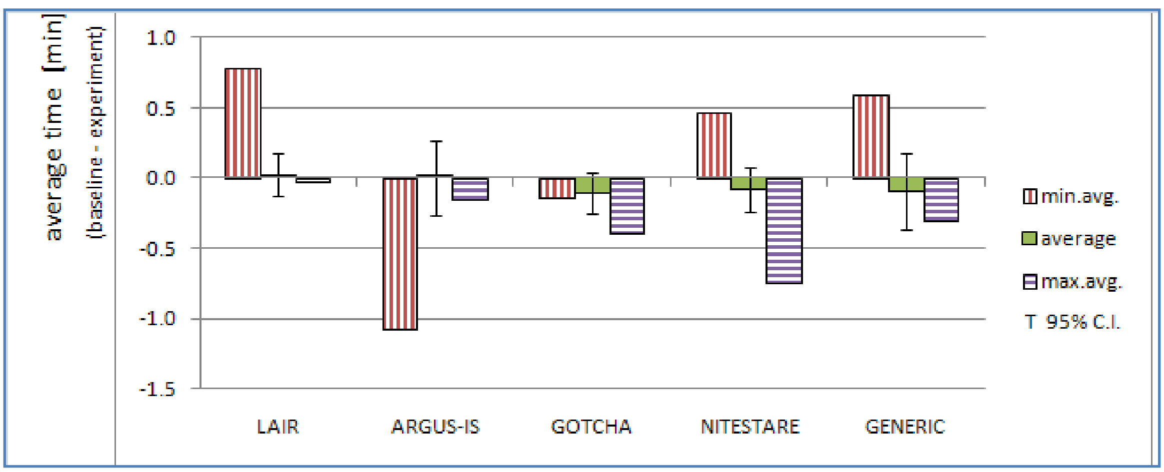


Figure 18. Experiment IE 1 Measure of Effectiveness

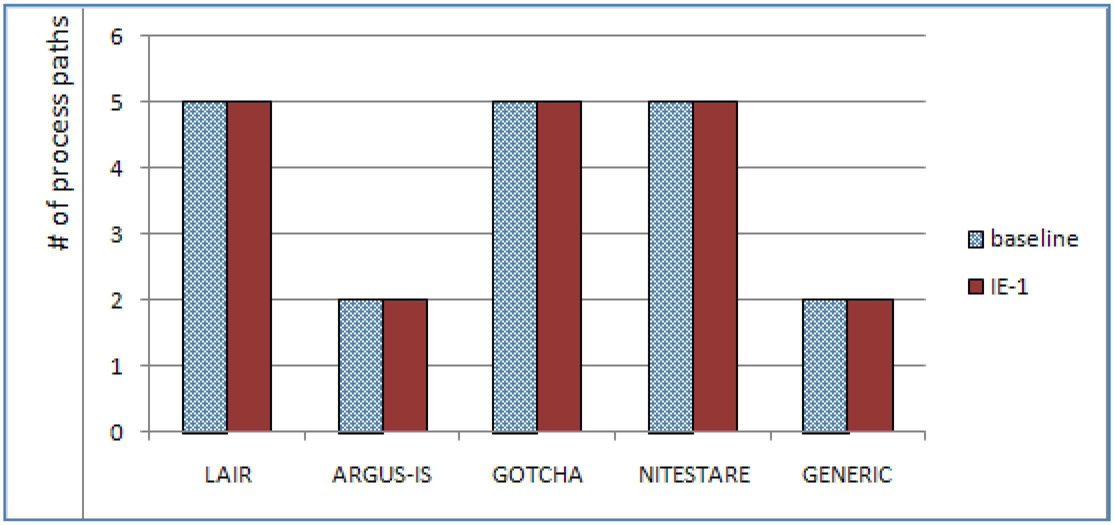


Figure 19. Experiment IE 1 Path Number Comparisons

Experiment IE 2: Ground Forces Receive Beyond Line of Sight Communications

Analytical Comments:

In this experiment an interoperability character state was changed so that the ground forces would have a new capability for communicating with the generic system and the CAOC. The character change caused an improvement in the interoperability measurement (see Table 12). The impact on generic system performance was mixed, however (see Figure 20).

Table 12. Experiment IE 2 Interoperability Measurement

	LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
ARGUS-IS	5/12	0	1/3	3/8	5/12	**13/24**	**13/24**
GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
NITESTARE	13/24	13/24	1/2	0	7/12	**5/8**	**19/24**
GENERIC	5/12	5/12	3/8	5/12	0	**5/8**	**5/8 (1/24)**
CAOC	**5/12**	**5/12**	**5/12**	**5/12**	**11/24**	**0**	**2/3 (1/24)**
GF	**5/12**	**5/12**	**5/12**	**5/12**	**11/24 (1/24)**	**11/24 (1/24)**	**0**

The explanation for mixed performance rests with the change in process paths (see Figure 21). Recall that the generic system has beyond-line-of-sight communications as a default configuration. As such, giving this same capability to the ground forces increased the number of process paths for the generic system from 2 to 18. The significant increase in number of process paths makes it difficult to compare MOE 3 results between the layered sensing baseline configuration and that contained in IE 2. Unless MOE 3 values are tracked for each process path, it is difficult to identify specific performance concerns.

These results further demonstrate that an improvement in interoperability measurement may not clearly or directly translate into an increase in mission effectiveness – at least not when evaluating architectures at this level of detail.

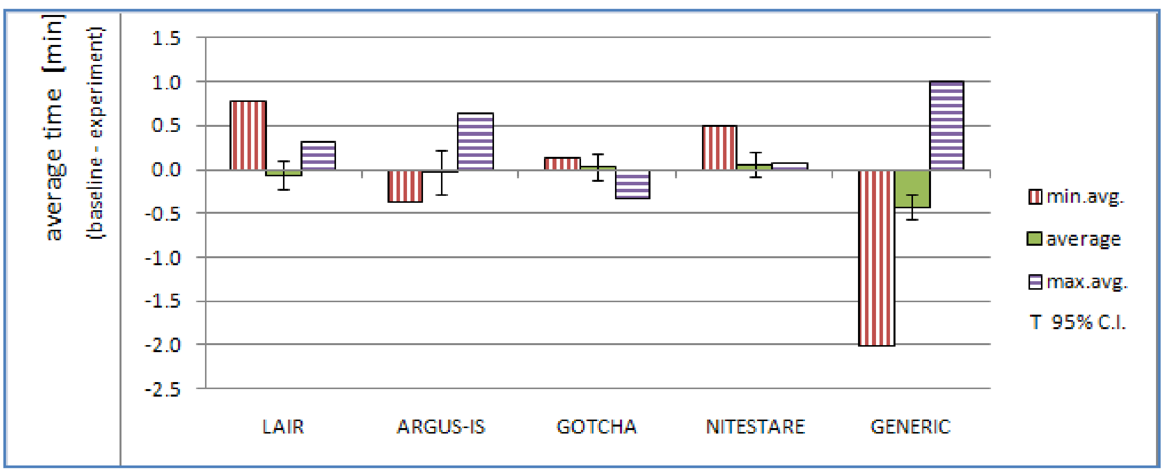


Figure 20. Experiment IE 2 Measure of Effectiveness

This experiment also helps validate simulation performance. The researchers would only expect significant changes in MOE 3 values for systems that saw a change in the number of process paths. In this case, significant MOE 3 changes were observed for

the generic system but not for the other four. This observation is consistent with the change in process path, so the discrete event simulation is performing as designed.

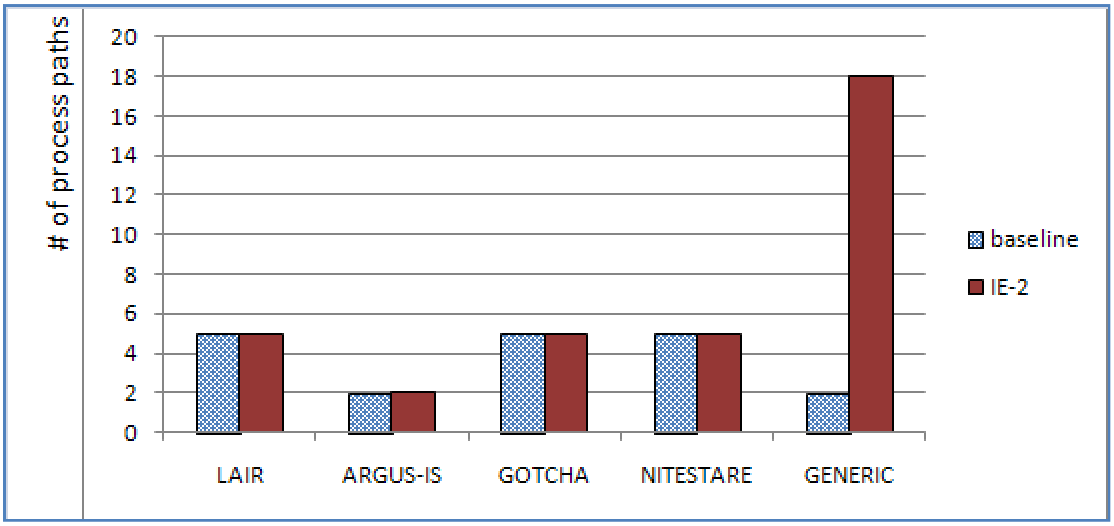


Figure 21. Experiment IE 2 Path Number Comparisons

Experiment IE 4: The CAOC System Is Placed within Line of Sight of the AOR

Analytical Comments:

No interoperability character states were changed in this experiment, so the interoperability measurement stayed constant. Moving the CAOC to within line-of-sight of the AOR represents an operational change. The intent behind IE 4 was to see if MOE 3 would change significantly when the interoperability measurement stayed constant. Figure 22 shows that at least some aspects of mission effectiveness (average time, minimum average time, or maximum average time) varied significantly. This observation is confirmed by Figure 23, which shows a marked increase in the number of process paths for all systems. This experiment shows that MOE 3 can change regardless of what happens to the interoperability measurement, further weakening the case for a consistent link between interoperability and mission effectiveness.

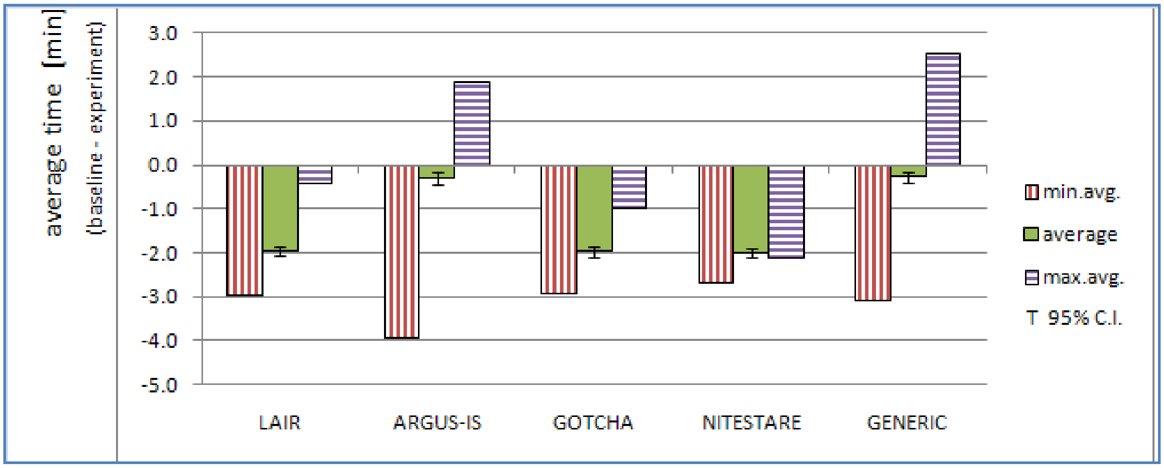


Figure 22. Experiment IE 4 Measure of Effectiveness

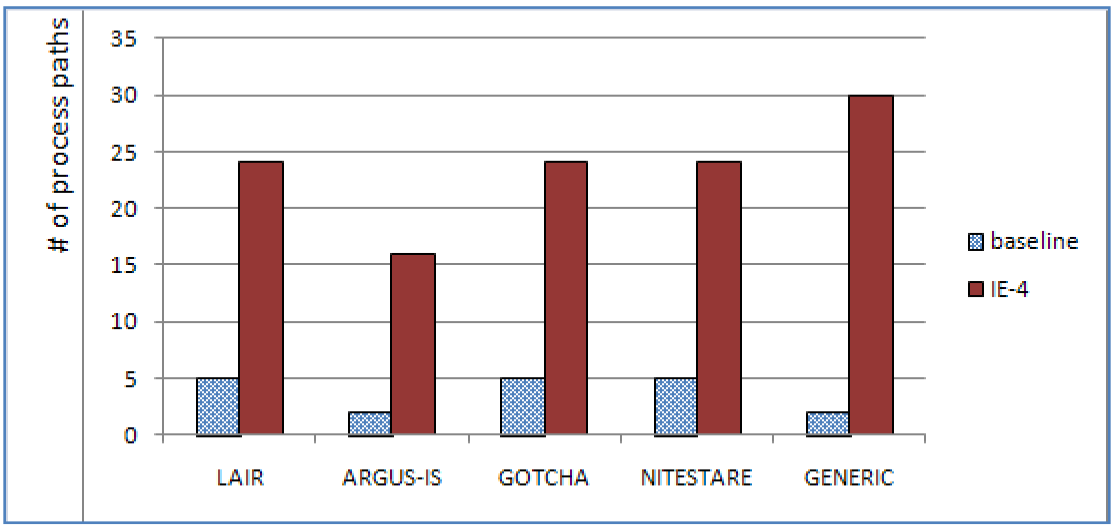


Figure 23. Experiment IE 4 Path Number Comparisons

Experiment IE 6: The Generic System Receives a Man-in-the-Loop

Analytical Comments:

For this experiment two interoperability character states were changed so that the generic system would have new analysis and dissemination capabilities that simulated a man-in-the-loop on the platform. Table 13 shows that the interoperability measurement improved as the generic system is more common with the CAOC and the ground forces. Figure 24 shows that mission effectiveness for the generic system also improved for all three plotted time values. Figure 25 shows that the number of process paths increased from 2 to 4.

Table 13. Experiment IE 6 Interoperability Measurement

	LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
ARGUS-IS	5/12	0	1/3	3/8	5/12	**13/24**	**13/24**
GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
NITESTARE	13/24	13/24	1/2	0	7/12	**5/8**	**19/24**
GENERIC	5/12	5/12	3/8	5/12	0	**17/24 (1/12)**	**2/3 (1/12)**
CAOC	**5/12**	**5/12**	**5/12**	**5/12**	**11/24**	**0**	**5/8**
GF	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**0**

IE 6 shows that even though improvements in the interoperability measurement may coincide with an increase in mission effectiveness, the magnitude of change in interoperability may not match that seen in effectiveness. Interoperability measurement changes on the order of one percent may occur in experiments that show a significant increase in the number of process paths. The change in path number, in turn, has ramifications for the MOE 3 values (explored in the next section).

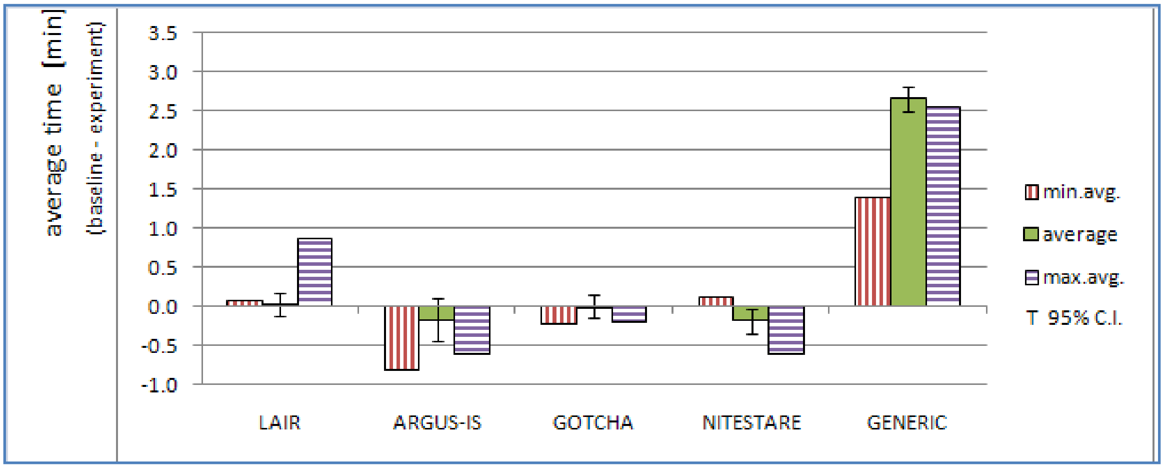


Figure 24. Experiment IE 6 Measure of Effectiveness

The results from these experiments support one conclusion: an improvement in interoperability measurement does not guarantee an improvement in mission effectiveness. Further, the extent to which the two are related cannot be determined until both components of the experiment are performed. In other words, a change in one category cannot be used to predict the extent of change in the other.

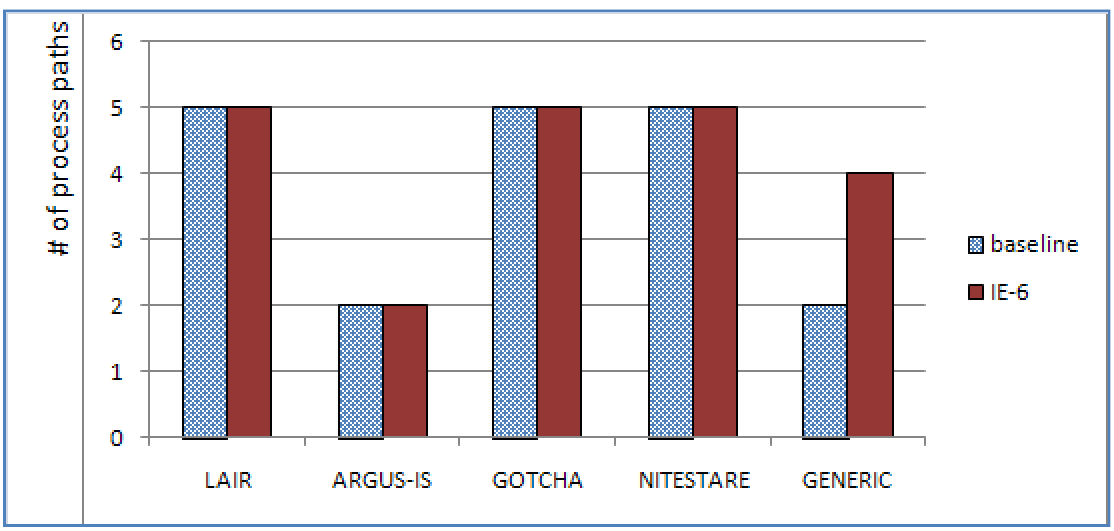


Figure 25. Experiment IE 6 Path Number Comparisons

This does not mean that the interoperability measure is flawed; it only means that the relationship between interoperability and mission effectiveness is more complex than originally thought. Other MOEs linked to interoperability may have showed different degrees of linkage. Interoperability character state representations more complex than the utilized Boolean scheme may also influence the results.

4.3 Process Paths

Failure to show a correlation between the interoperability measurement and the MOE linked to interoperability was disappointing, at least initially. However, the effort put into the investigation did lead to a deeper appreciation for the significance of process paths. This new appreciation produced a significant finding which is described in this section.

Recall that in experiment IE 6 the generic system was given the capability to analyze and disseminate data. This capability change increased the number of process paths from 2 to 4. Figure 26 and Figure 27 show the baseline and IE 6 process paths for the generic system.

The new generic system capabilities allowed more of the ISR process to be completed on the platform. As was the design intent during discrete event simulation construction, performing more steps of the ISR process on the platform decreased the amount of time it takes to get data to the ground forces. As Figure 28 and Figure 29 show, the change in mission performance can be significant.

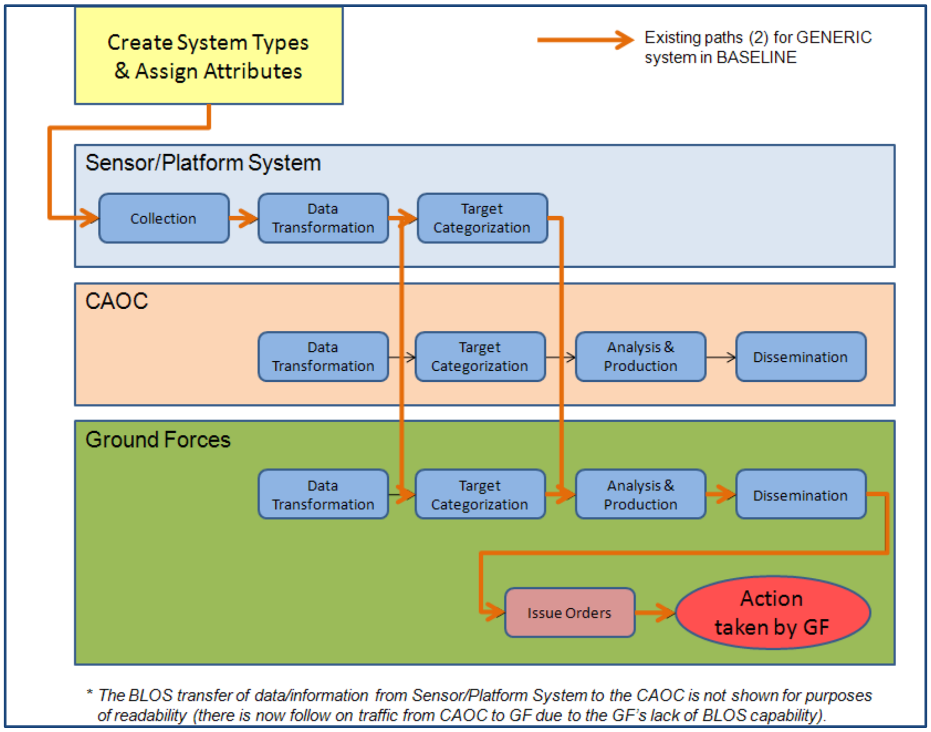


Figure 26. Baseline Process Paths for the Generic System

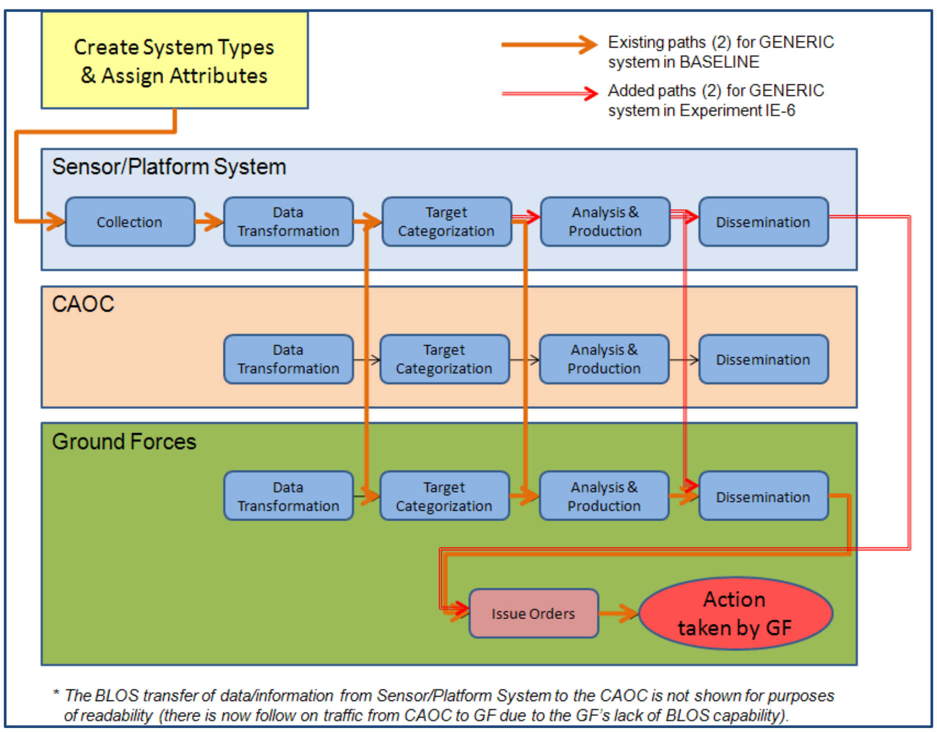


Figure 27. IE 6 Process Paths for the Generic System

The process path in IE 6 (path 4 in Figure 28) that took the shortest time to complete was approximately 6 minutes 40 seconds faster than the fastest process path in the baseline (path 2 in Figure 28). Interpreting this result literally means the experimental architecture improved MOE 3 by 42%. Further, executing a 2-sample T-distribution test with unequal variances and 365 degrees of freedom allows the researchers to conclude that the average times for path 2 and path 4 are indeed different in a statistically significant sense, with a confidence level exceeding 99.95%. (10:336 – 349, 700) This experimental observation has interesting implications – not for generic platform performance, but for ISR process execution.

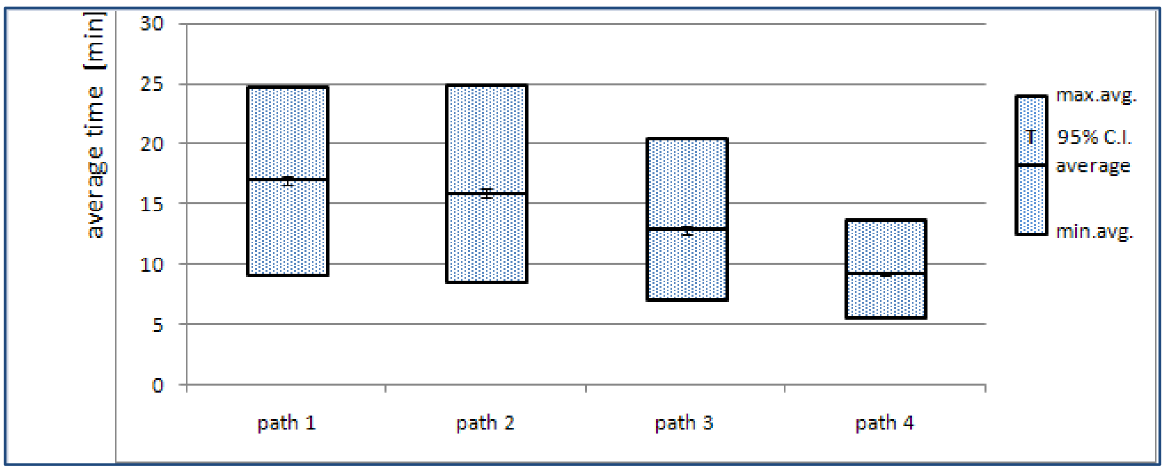


Figure 28. Time to Get Data from System to Ground Forces

Figure 29 shows performance for paths 2 through 4 as compared to path 1. The data show that layered sensing performance improves significantly as more of the ISR process is performed on the platform collecting the intelligence information. Although tempting to make, this conclusion is inappropriate. The time distributions for completing the various ISR processes that were input into the discrete event simulation are certainly plausible but they may not adequately address all possible scenarios. As such, it is better

to use the data to show that process execution, in general, is an important component of interoperability.

Building on this point allows one to consider that interoperability, at least for ISR-like processes, is more than determining how many sensor types should go on any one platform or what type of communications capabilities a platform should have. Interoperability is more than system design; mission success may actually hinge on finding the correct location in the system of systems architecture for executing each part of the process.

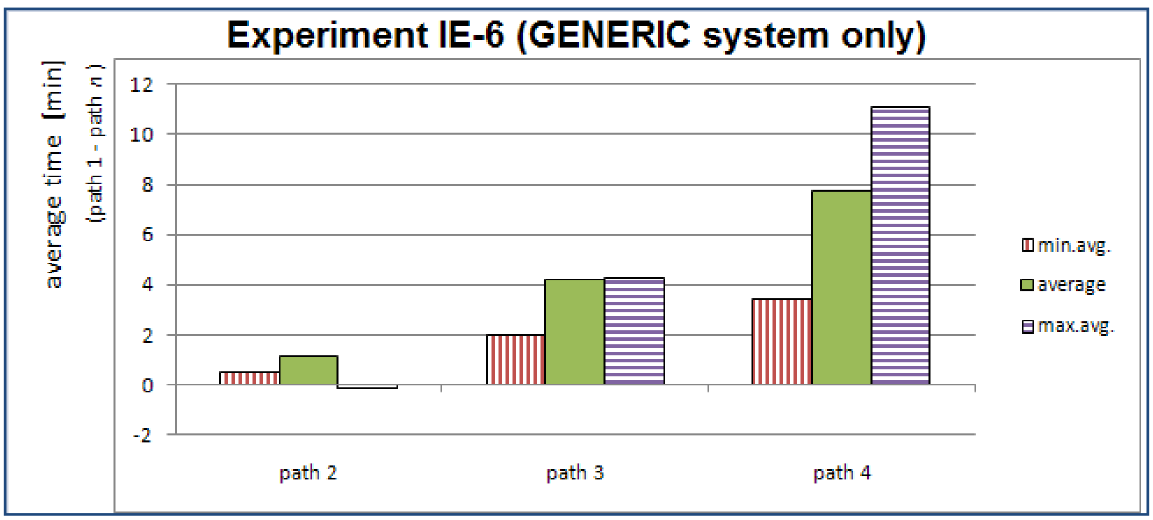


Figure 29. Process Path Performance Differences

If one considers that each step in the ISR process captures or manipulates data in a manner that prepares that data for reception by the next step, than the efficiency of step-to-step coupling becomes an important component of interoperability. The results from IE 6 certainly seem to indicate a need for further study and quantification of process path impact as part of the overall effort to characterize interoperability. It is possible that

successful process path design and implementation may actually contribute more to interoperability than changes in hardware or software configurations.

4.4 Measures of Effectiveness Versus Measures of Performance

Selecting the correct MOEs for evaluating layered sensing performance was an important part of the research effort. Despite the level of effort put into MOE selection at the beginning of the project, the task turned out to be more challenging than initially expected. The first challenge appeared during the early stages of simulation execution. Of the 6 MOEs obtained by AFIT and vetted by AFRL/RY, only one (MOE 3) showed a direct link to interoperability. This situation was tolerable for two reasons. First, the other MOEs may not have been related to interoperability but they were still important to AFRL. Second, time for data to travel from collection by the sensor to action by the ground forces (MOE 3) was a solid benchmark metric for layered sensing performance.

As the discrete event simulation matured it became clear that capturing MOE 3 in a meaningful manner was going to present another challenge. Ideally, the researchers wanted a MOE that captured mission effectiveness for all of layered sensing, not just platforms or sensors that were part of the architecture. Previous depictions of MOE 3 have listed average, minimum average, and maximum average time values for each of the five systems included in the layered sensing architecture. For purposes of this discussion, Figure 30 sums the times for all systems into one composite plot of average, minimum average, and maximum average times for the baseline configuration and IE 6.

Inspection of this figure shows little difference in mission effectiveness. Granted, the average performance for the experimental architecture improved by approximately

28 seconds. This observation is reinforced by executing a 2-sample T-distribution test with unequal variances and 2269 degrees of freedom. The test results allow the researchers to conclude that the average times for the baseline and IE 6 are indeed different in a statistically significant sense, with a confidence level exceeding 97.5%. (10:336 – 349, 700) Despite having a statistically significant difference, the improvement seems so slight that architectural changes captured in IE 6 are hardly worth considering. If inspection of IE 6 results stopped here, significant insight would be lost.

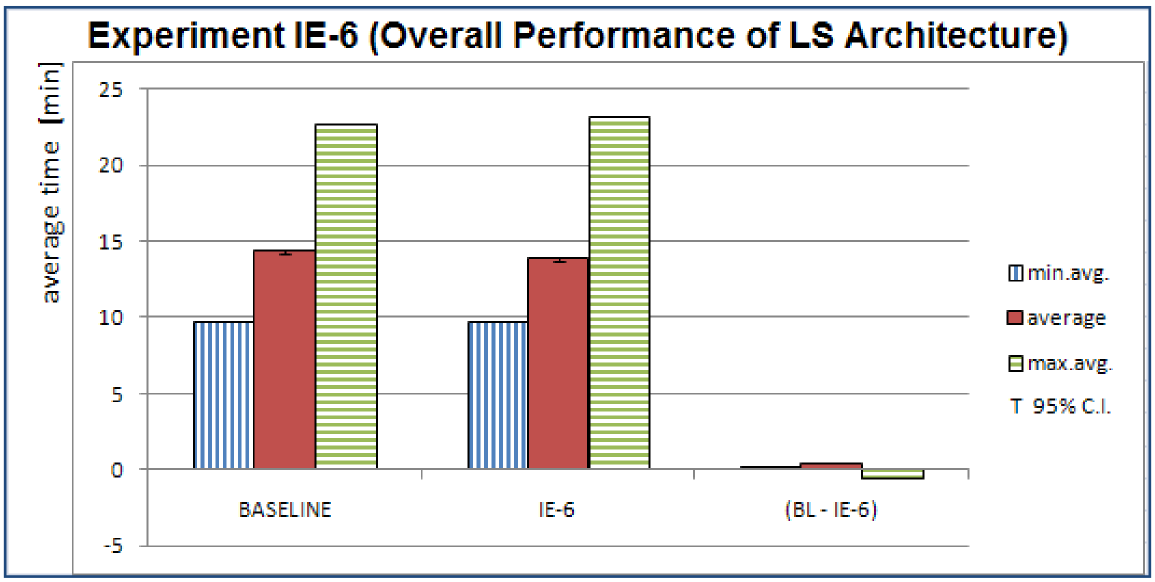


Figure 30. Overall Performance for Layered Sensing

Inspection of Figure 24 shows that IE 6 does indeed show improved performance, at least for the generic platform and sensor that saw changes in interoperability character states. Although an important observation had been garnered, it came with a cost. This cost was a drift in measurement from MOE to MOP. The condition is further acerbated by tracking performance for specific process paths, as shown in Figure 28. Admittedly, this is not an ideal systems engineering construct. However, this deflection from the

desirable is tolerated because measuring performance for layered sensing as a holistic entity did not capture the fine detail needed to understand the simulation results. Had this condition been anticipated at the beginning of the effort, different approaches for measuring effectiveness may have been implemented.

The researchers argue that the use of MOPs has merit. Limiting changes in character states for experimental trials to a single system helped track changes and quantify performance in meaningful ways. Ultimately, changes to a single system stood as surrogates for changes to the entire architecture. Experiments were run with interoperability character state changes for all systems. The result was a large increase in the number of possible process paths (as high as 92 in some cases). Some of the new paths performed better, but many did not. Averaging across systems prevented the researchers from identifying specific paths that performed better as a result of changes to one or a small number of interoperability character states. Valuable insight would have been lost had performance not been tracked by both MOE and MOP.

4.5 Measures of Effectiveness for Mission Resources

This section presents data samples produced by the mission resource experiments described in Table 9. The data presentation is broken down by MOE. The results of experiments ME 1 through ME 4 are listed in the plot shown for each MOE, as is the baseline value. The data shows how the simulation can evaluate layered sensing system performance for MOEs that are not only related to interoperability measurements.

MOE 1 and MOE 6: Percentage of Time Mission Is Covered by at Least One Platform and Percentage of Time Mission Covered by at Least Two Platforms

The line in the center of each blue bar in Figure 31 and Figure 32 is the average percentage of mission coverage by the indicated number of sensors. The bar endpoints are average minimum and maximum values. The endpoints of the lines are extreme minimum and maximum values. The 95% confidence levels have been plotted for the average values shown on each figure.

Analytical Comments:

Figure 31 shows that experiments run for MOE 1 do not stress the layered sensing architecture with regards to mission coverage by at least one system. Coverage by at least two different sensors – an objective input by AFRL/RY – is more challenging. In the case of experiment ME 4 (shown on Figure 32), where the number of systems available for the modeled use case dropped from 15 to 11, performance may not meet mission needs. Adding an IR capability to an E/O system (ME 1 in Figure 32) shows an increase in system performance, which is to be expected. These observations are reinforced by executing a 2-sample T-distribution test with unequal variances and 434 or 487 degrees of freedom. The statistical analysis shows that the difference in average times between the baseline and ME 1 and the baseline and ME 4 are statistically significant, with confidence levels of 95%. (10:336 – 349, 700)

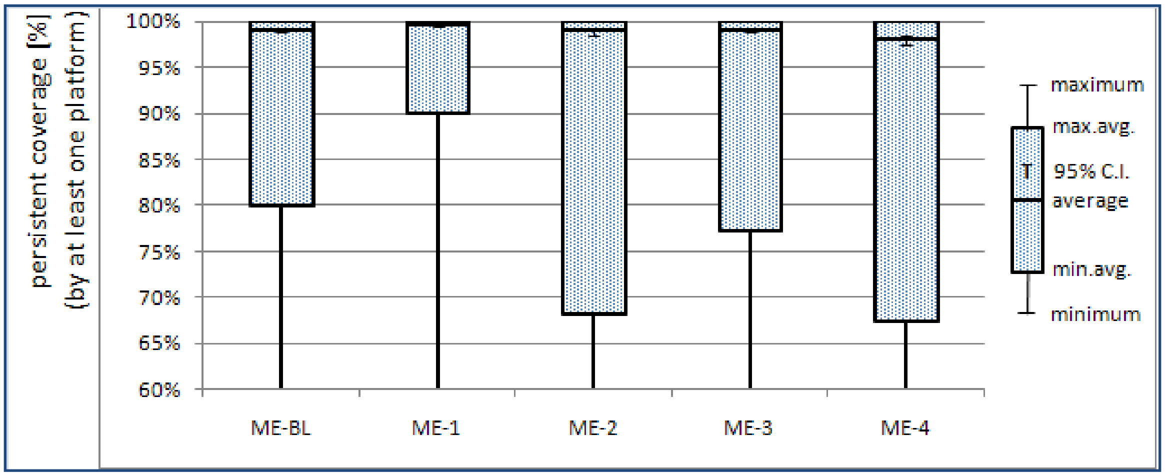


Figure 31. Mission Coverage by at Least One Sensor

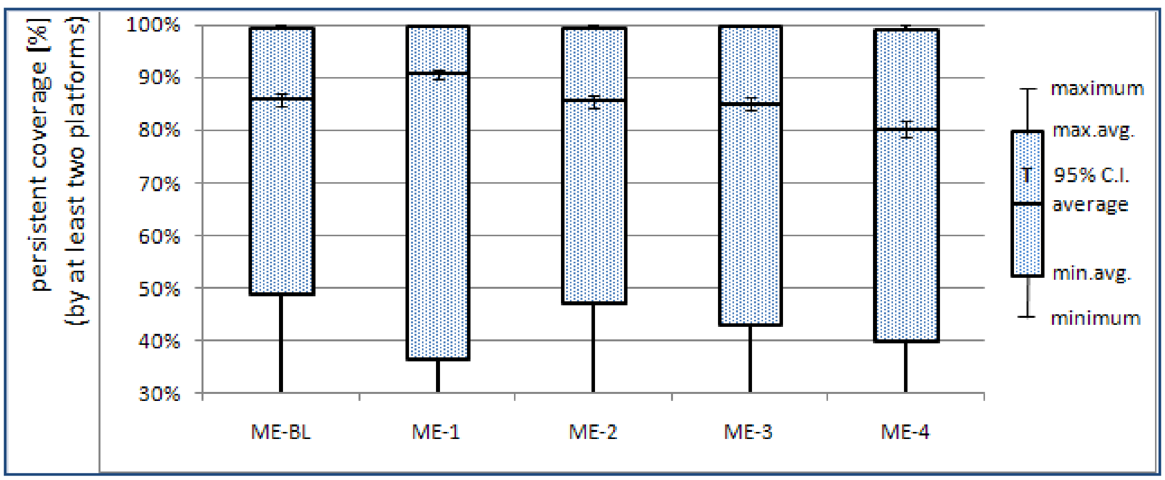


Figure 32. Mission Coverage by at Least Two Different Sensors

MOE 4: Layered sensing mission failures in a 24-hour period

The line in the center of each blue bar in Figure 33 is the average number of system failures for a 24-hour mission. The bar itself starts at the minimum average failure value and goes to the maximum average failure value. The 95% confidence levels are included for the average values.

Analytical Comments:

Figure 33 shows that the conditions for experiment ME 2 caused a minor failure rate change from the baseline. None of the experiments showed a significant operational change. Although this particular set of experiments did not impact the MOE, other user-defined experiments might cause significant changes. Regardless, it is an important MOE for evaluating system performance.

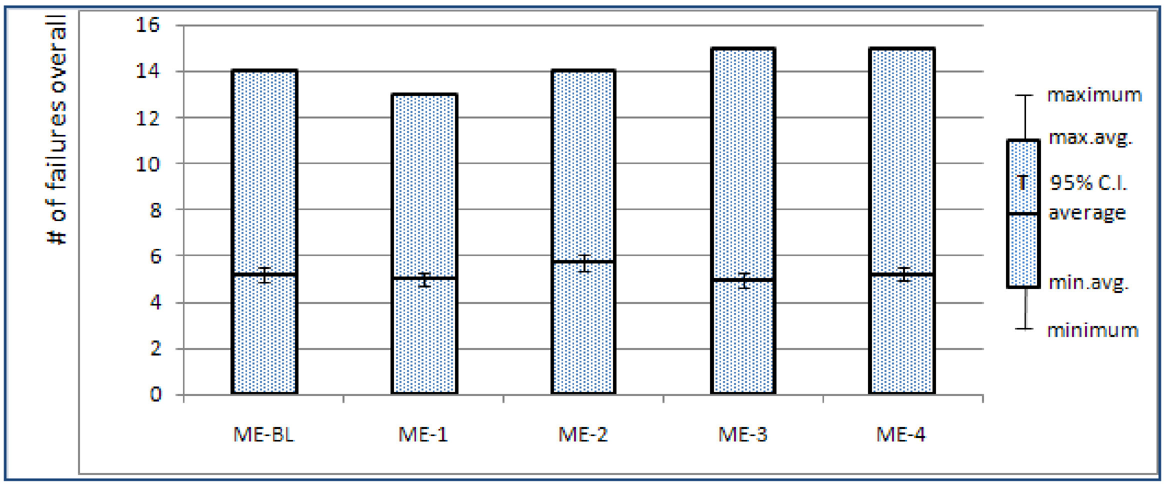


Figure 33. Sensor/Platform System Failures per 24-hour Mission

MOE 5: Average time taken to begin mission coverage

The line in the center of each blue bar in Figure 34 is the average time it takes for two systems to begin mission coverage (an MOE objective supplied by the sponsor). The bar endpoints are average minimum and maximum values. The endpoints of the lines are extreme minimum and maximum values. The 95% confidence levels are plotted for the average values even though the intervals are too small to be seen on the display.

Analytical Comments:

For this MOE, decreasing the total number of systems available to layered sensing from 15 to 11 (experiment ME 4) increased the amount of time required to begin event coverage. In fact, the time to begin coverage nearly doubled – a result not likely acceptable to the ground forces. Analysis shows that the baseline and ME 4 average times are different in a statistically significant sense. Experiments such as this may help AFRL/RY calculate a minimum acceptable number of systems needed for layered sensing success, given a specific basing configuration and AOR size.

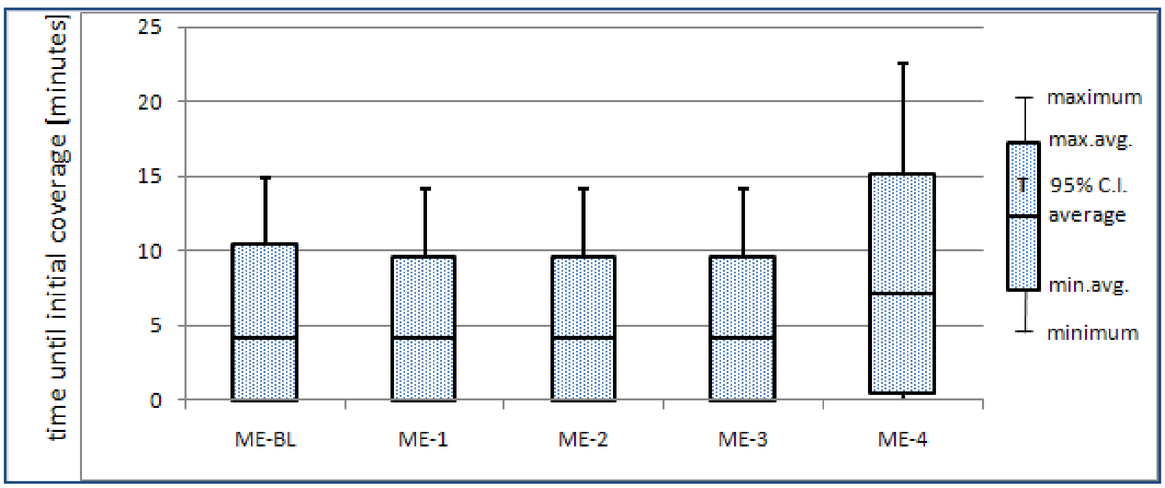


Figure 34. Average Time to Begin Mission Coverage

5. Conclusions and Recommendations

5.1 Overview

This chapter contains a concise discussion of the research contributions and significance to the broader DoD community. Recommendations for future action and research are also entertained.

5.2 Research Contributions

The differences between the intended and actual flow of research activity must be discussed before the contributions can be put in proper context. Figure 35 shows the intended activity flow for this effort. There were two parallel processes. The first process attempted to characterize a suspected correlation between interoperability measurements and system interoperability MOE values. As noted previously, the correlation never materialized.

The second process attempted to capture mission resource MOEs. This part of the experiment worked as planned.

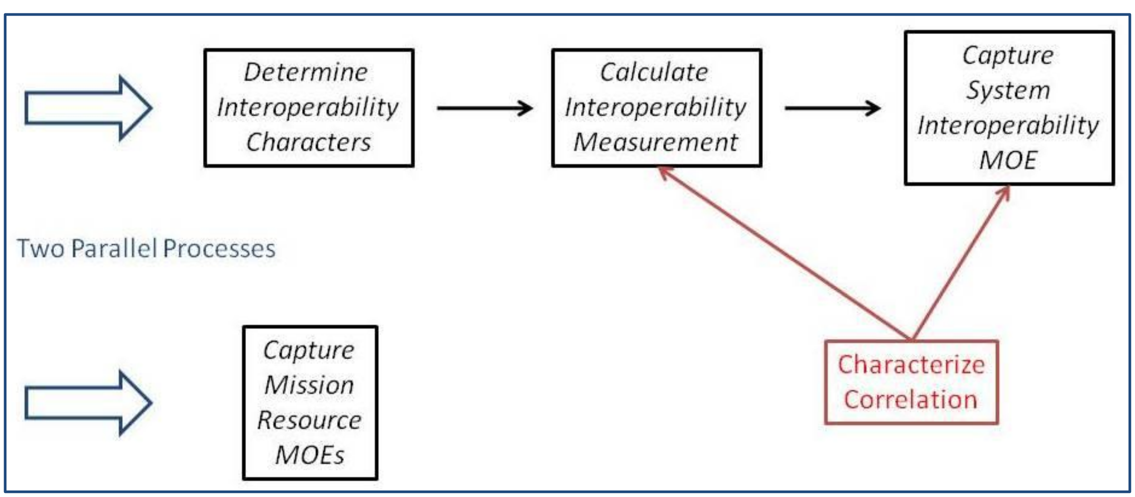


Figure 35. Intended Research Activity Flow

Figure 36 shows the actual flow of research activity. As the first process was executed, the concept of a process path formed and grew in importance. The relationship between determining interoperability characters, calculating interoperability measurements, and capturing the number of process paths was well understood. The influence of process path on interoperability MOEs and MOPs was not completely characterized and requires further research.

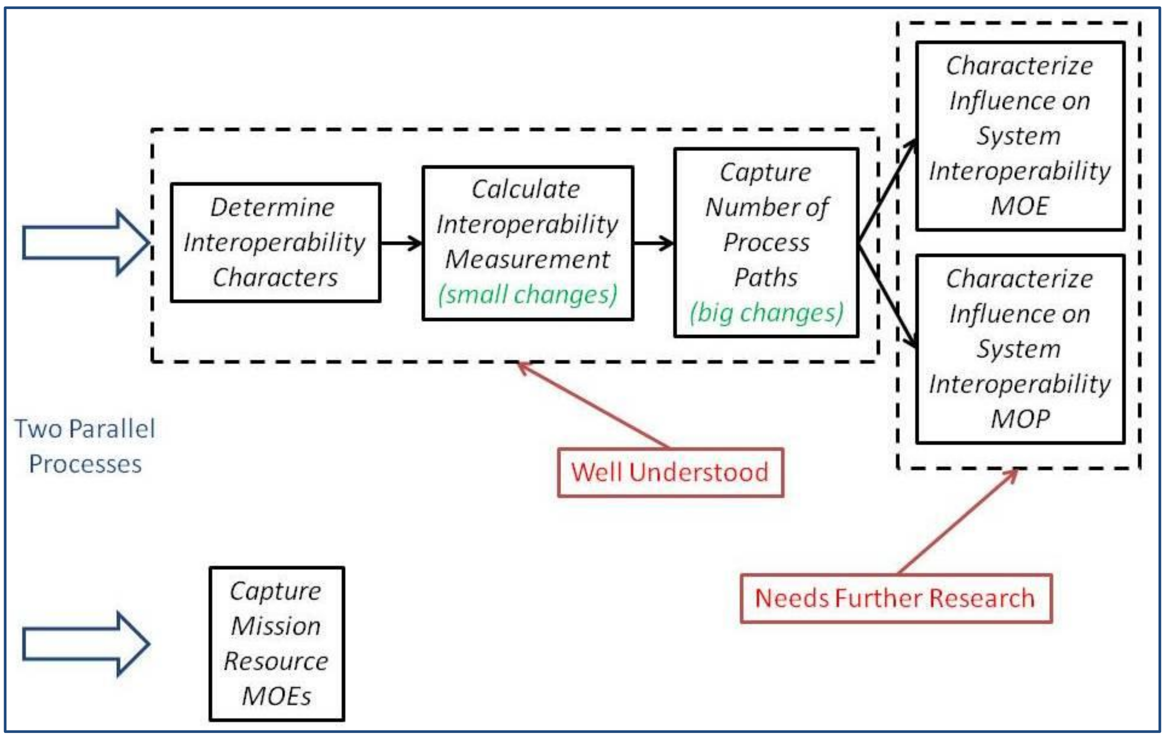


Figure 36. Actual Research Activity Flow

Having described the activity flow, the research contributions can now be listed:

1. The relationship between interoperability character identification and measurement for collaborative interoperability scenarios was adequately demonstrated.

2. Interoperability measurements do not always reflect the same magnitude of change as that seen for number of process paths. Small changes in interoperability

measurement (caused by changes in only one or two interoperability character states) may generate large changes in the number of process paths available to the system. Further, large changes in the number of process paths may lead to large changes in MOE or MOP values.

3. For net-centric processes like those found in ISR systems, process paths may be an important component of quantitative interoperability measurement techniques.

4. The number and type of process paths present in a system of systems may be reflected in MOEs and MOPs, but this subject requires further exploration.

5.3 Research Significance

This research is significant because it demonstrates that the interoperability measurement technique derived by Ford in 2008 can be extended to cases involving collaborative interoperability through the use of discrete event simulations. Care must be given to the selection of interoperability characters and the MOEs used to grade system performance.

Regardless of the constraints on this research effort, it constitutes a positive contribution to the DoD effort to quantify interoperability. The degree to which current and future fielded military systems reach goals linked to interoperability will remain unknown unless methods for measuring interoperability are developed, used, and analyzed. This graduate research project demonstrates progress towards this end.

5.4 Recommendations for Action

Although an overall application of the interoperability measurement method in the sense of evaluating different architectures has been demonstrated, the requirement for

more action on this topic exists. The current effort could be supplemented by further combining the abilities of AFIT and AFRL: additional structure and depth of system characterization emphasizing interoperability measurement should be fostered by AFIT whereas AFRL could contribute by providing expertise for large scale visual simulation. The suite of simulation tools currently under development by the AFRL/RY is especially attractive. Instantiation of the interoperability characters is the vital link between both efforts. The call for action on this topic must be heeded in order to successfully characterize the depth of interoperability character impact on selected MOEs.

5.4 Recommendations for Future Research

Recommendations for future research include the following topics and areas of interest:

1. Build discrete event simulations and determine appropriate MOEs for additional use cases of interest to AFRL.
2. Explore ways to capture more complete sets of interoperability characters. One possible avenue is adding levels of complexity to the characters.
3. Use or derive more complex representations for interoperability character states (do not rely entirely on presence/absence representation).
4. Craft more robust simulations and execute more robust MOE identification and calculation schemes. Incorporate more than one interoperability related MOE.
5. Fully characterize the role played by the process path in quantitative interoperability analyses.

5.5 Summary

The methodology described in Chapter 3 and the results discussed in Chapter 4 show that changes in architecture can possibly be linked to changes in mission effectiveness some of the time. Also, the role of the process path and its relationship to interoperability require further exploration. The experimental components were faithfully executed for the mission thread and scenario of interest. Interoperability measurements and MOE values were obtained. Experiments were analyzed and results were presented. Taking into account the project scope and available resources, the graduate research project is deemed a success.

A1. Use Cases

This appendix contains the three use cases developed during discussions with AFRL/RY. Recall that UC 2 was the use case simulated with the Arena software.

Use Case ID	UC 1 (Event Tip-off Determination)
Operational Thread (Scope)	Urban Surveillance
Level	Tactical
Primary Actor	Platform crew, CAOC/JAOC/JOC personnel, ground forces
Secondary Actors	CFACC/JFACC/JFC, environment, threat, jamming threat, communications, operating base personnel
Stakeholders and Interests	Platform Crew: Must be able to successfully and safely operation sensor-equipped platforms, must be able to communicate with and respond to tasking from CAOC/JAOC/JOC and ground forces personnel. CAOC/JAOC/JOC Personnel: Must task layered sensing platforms and sensors to collect data describing objectives and targets of interest, must be able to analyze collected data, must be able to disseminate findings to ground forces Ground Forces: Require operational guidance garnered from analysis of data provided by layered sensing system CFACC/JFACC: Must have capability to task and receive data from platforms and sensors to support forces in theater JFC: Needs adequate ISR capabilities to support operational/theater campaign
Brief Description	The CFACC/JFACC tasks the CAOC/JAOC/JOC to survey theater battlespace. The CAOC issues an ops order to the base of operations. The base of operations launches a platform equipped with the appropriate sensor. The platform transitions to the surveillance area. Once in the surveillance area the platform locates the objective and any appropriate targets. The sensor collects intelligence data. The platform transmits the data to the system ground site. The ground site relays sensor data to the CAOC. The CAOC analyzes the data. An event tip-off is observed. The analysis results are disseminated to the appropriate actors.
Preconditions	Infrastructure, systems, and personnel are already in-place and ready to conduct operations
Post-conditions	Intelligence data is stored and accessible by authenticated personnel. Results of data analysis are passed to appropriate secondary actors.
Flow of Events	N/A
Alternative Flows and Exceptions	1. Mission deviations due to environmental constraints 2. Mission deviations due to threats in the operating area 3. Mission deviations due to communications jamming in the operating

	area The various constraints may result in either mission delay or cancellation. In either case, contingency planning in the CAOC/JAOC/JOC will deal with deviations from the happy path.
Non-behavior Requirements	Primary metric is MOE 3 (see Table 3, Chapter 2)
Special Requirements	N/A
Technology and Data Variation List	Interoperability characters (see Table 4, Chapter 2)

Use Case ID	UC 2 (Unplanned Event Reaction)
Operational Thread (Scope)	Urban Surveillance
Level	Tactical
Primary Actor	Platform crew, CAOC/JAOC/JOC personnel, ground forces
Secondary Actors	CFACC/JFACC/JFC, environment, threat, jamming threat, communications, operating base personnel
Stakeholders and Interests	Platform Crew: Must be able to successfully and safely operation sensor-equipped platforms, must be able to communicate with and respond to tasking from CAOC/JAOC/JOC and ground forces personnel. CAOC/JAOC/JOC Personnel: Must task layered sensing platforms and sensors to collect data describing objectives and targets of interest, must be able to analyze collected data, must be able to disseminate findings to ground forces. Ground Forces: Require operational guidance garnered from analysis of data provided by layered sensing system CFACC/JFACC: Must have capability to task and receive data from platforms and sensors to support forces in theater JFC: Needs adequate ISR capabilities to support operational/theater campaign
Brief Description	The CFACC/JFACC tasks the CAOC/JAOC/JOC to survey theater battlespace. The CAOC issues an ops order to the base of operations. The base of operations launches a platform equipped with the appropriate sensor. The platform transitions to the surveillance area. Once in the surveillance area the platform locates the objective and any appropriate targets. The sensor collects intelligence data. The platform transmits the data to the system ground site. The ground site relays sensor data to the CAOC. The CAOC analyzes the data. The analysis results are disseminated to the ground forces so that actions can be taken to mitigate impact from unplanned events.
Preconditions	Infrastructure, systems, and personnel are already in-place and ready to

	conduct operations
Post-conditions	Intelligence data is stored and accessible by authenticated personnel. Results of data analysis are passed to appropriate secondary actors.
Flow of Events	N/A
Alternative Flows and Exceptions	1. Mission deviations due to environmental constraints 2. Mission deviations due to threats in the operating area 3. Mission deviations due to communications jamming in the operating area The various constraints may result in either mission delay or cancellation. In either case, contingency planning in the CAOC/JAOC/JOC will deal with deviations from the happy path.
Non-behavior Requirements	Primary metric is MOE 3 (see Table 3, Chapter 2)
Special Requirements	N/A
Technology and Data Variation List	Interoperability characters (see Table 4, Chapter 2)

Use Case ID	UC 3 (Forensic Analysis)
Operational Thread (Scope)	Urban Surveillance
Level	Tactical
Primary Actor	Platform crew, CAOC/JAOC/JOC personnel, ground forces
Secondary Actors	CFACC/JFACC/JFC, environment, threat, jamming threat, communications, operating base personnel
Stakeholders and Interests	Platform Crew: Must be able to successfully and safely operation sensor-equipped platforms, must be able to communicate with and respond to tasking from CAOC/JAOC/JOC and ground forces personnel. CAOC/JAOC/JOC Personnel: Must task layered sensing platforms and sensors to collect data describing objectives and targets of interest, must be able to analyze collected data, must be able to disseminate findings to ground forces Ground Forces: Require operational guidance garnered from analysis of data provided by layered sensing system CFACC/JFACC: Must have capability to task and receive data from platforms and sensors to support forces in theater JFC: Needs adequate ISR capabilities to support operational/theater campaign
Brief Description	The CFACC/JFACC tasks the CAOC/JAOC/JOC to survey theater battlespace. The CAOC issues an ops order to the base of operations. The base of operations launches a platform equipped with the appropriate sensor. The platform transitions to the surveillance area.

	Once in the surveillance area the platform locates the objective and any appropriate targets. The sensor collects intelligence data. The platform transmits the data to the system ground site. The ground site relays sensor data to the CAOC. The CAOC analyzes the data. The analysis results are disseminated to the appropriate actors.
Preconditions	Infrastructure, systems, and personnel are already in-place and ready to conduct operations
Post-conditions	Intelligence data is stored and accessible by authenticated personnel. Results of data analysis are passed to appropriate secondary actors.
Flow of Events	N/A
Alternative Flows and Exceptions	1. Mission deviations due to environmental constraints 2. Mission deviations due to threats in the operating area 3. Mission deviations due to communications jamming in the operating area The various constraints may result in either mission delay or cancellation. In either case, contingency planning in the CAOC/JAOC/JOC will deal with deviations from the happy path.
Non-behavior Requirements	Primary metric is MOE 3 (see Table 3, Chapter 2)
Special Requirements	N/A
Technology and Data Variation List	Interoperability characters (see Table 4, Chapter 2)

A2. Joint Capability Area Interoperability Character Definitions

The following JCA-provided definitions provide more meaning for the experimental interoperability characters.

2 Battlespace Awareness – The ability to understand dispositions and intentions as well as the characteristics and conditions of the operational environment that bear on national and military decision-making.

2.1 Intelligence, Surveillance and Reconnaissance – The ability to conduct activities to meet the intelligence needs of national and military decision-makers.

2.1.2 Collection – The ability to obtain required information to satisfy intelligence needs.

2.1.2.3 Imagery Collection – The ability to obtain information from the visible and non-visible spectrum based on the likeness or visual presentation of any natural or man-made feature, object, or activity.

2.1.2.3.1 Electro-Optical Imagery Collection – The ability to gather information from a visual presentation derived from the ultraviolet through far infrared electromagnetic spectrum.

2.1.2.3.1.1 Panchromatic Collection – The ability to obtain a visual presentation from the visible spectrum of any natural or man-made feature, object, or activity.

2.1.2.3.1.2 Infrared Collection – The ability to obtain a likeness or visual presentation from the Infrared spectrum of any natural or man-made feature, object, or activity.

2.1.2.3.2 RADAR Imagery Collection – The ability to derive information from a visual presentation produced by recording radar waves from a given object within the radiofrequency spectrum.

2.1.3 Processing / Exploitation – The ability to transform collected information into forms suitable for further analysis or action.

2.1.3.1 Data Transformation – The ability to select, focus, simplify, tag and transform overtly or covertly collected data into human or machine interpretable form for collaboration across the ISR community for further analysis or other action.

2.1.3.2 Objective / Target Categorization – The ability to identify, classify and verify objectives/targets enabling further analysis or action.

2.1.4 Analysis and Production – The ability to integrate, evaluate, and interpret information from available sources and develop intelligence products that enable situational awareness.

2.1.5 Intelligence, Surveillance and Reconnaissance Dissemination – The ability to present information and intelligence products that enable understanding of the operational environment to military and national decision-makers.

5 Command and Control – The ability to exercise authority and direction by a properly designated commander or decision maker over assigned and attached forces and resources in the accomplishment of the mission.

5.5 Direct – The ability to employ resources to achieve an objective.

5.5.2 Task – The ability to direct actions and resources.

5.5.2.1 Synchronize Operations – The ability to arrange actions through established links with mission partners to ensure coordination of operations.

5.5.2.2 Issue Plans – The ability to provide relevant plans.

5.5.2.3 Issue Orders – The ability to provide directives.

6 Net-Centric – The ability to provide a framework for full human and technical connectivity and interoperability that allows all DoD users and mission partners to share the information they need, when they need it, in a form they can understand and act on with confidence, and protects information from those who should not have it.

6.1 Information Transport – The ability to transport information and services via assured end-to-end connectivity across the NC environment.

6.1.2 Wired Transmission – The ability to transfer data or information with an electrical/optical conductor.

6.1.2.1 Line of Sight – The ability to exchange data or information via electromagnetic spectrum within line of sight.

6.1.2.2 Beyond Line of Sight – The ability to exchange data or information via electromagnetic spectrum beyond line of sight.

A3. Matlab Code for Interoperability Measurement Calculation

The Matlab code that implements Ford's interoperability measurement is shown below:

```
% ****************************************************
% Sim(BIN) for directional interoperability measurement
% ****************************************************

clc;
myxiFORD = xlsread('characters', -1);
  % opens file 'characters.xls' (in same folder) to allow for array selection and input

[characters,systems] = size(myxiFORD);
  % define size of the system instantiation matrix Xi
systems = systems/2;
  % define number of systems (only half due to transmit and receive half of matrix)
Imatrix = zeros(systems,systems);
  % initially set Xi matrix to zeros

for transmit = 1:systems
   for receive = systems+1:systems*2
      if (transmit ~= receive-systems)
         % automatically leaves system to system comparison at value zero
         b1 = bitand(myxiFORD(1:characters,transmit),myxiFORD(1:characters,receive));
         % bitwise AND comparison
         Imatrix(transmit,receive-systems)= sum(b1)/(characters);
      end
   end
end

disp('Interoperability Character Matrix (Instantiation of S):');
disp('-------------------------------------------------------');
disp(myxiFORD);
disp(' ');
disp('Matrix Size: '); disp(size(myxiFORD));
disp(' ');

disp('Interoperability Matrix I:');
disp('--------------------------');
disp(Imatrix);
disp(' ');

disp('Mean Interoperability Value:');
disp('------------------------------');
disp(sum(sum(Imatrix))/(numel(Imatrix)-systems));
```

A4. Comments on the Interoperability Measurement Technique

Consistency of system characters through different levels

With regards to the measurement of directional interoperability Ford chose to instantiate a given set of systems S as $\sum = \{ \sum_T, \sum_R \}$ using a hierarchical breakdown of interoperability characters. These characters were methodically derived from several publications and doctrines and successively described by binary states. Although not defined or stated by Ford, it is to the understanding of this group that the presence of a given character state (i.e. $x_i(s_j) = 1$) at a lower level within the hierarchy automatically results in the appropriate character's state at the higher level(s) to be present as well. Using Ford's application on SEAD (6:81-92) this can be explained along the following sample:

- The interoperability character "C2" is explained by "command & control / be commanded & controlled" (6:86, table 16).
- The interoperability character "C2.Comm" is explained by "communicate(T) / communicate(R)" (6:86, table 16).
- The interoperability character "C2.Comm.Red" is explained by "communicate(T) on red channels / communicate(R) on red channels" (6:86, table 16).
- The ability of IADS1 and IADS2 to communicate (T & R) on red channels is obvious and therefore described with the character states $x_{C2.Comm.Red}(s_{IADS1}) = 1$ and $x_{C2.Comm.Red}(s_{IADS2}) = 1$ (6:88, table 17).
- Accordingly the character states at the higher levels C2 and C2.Comm are set to 1 as well (if a system can communicate utilizing a certain channel it can clearly be followed that the same system is able to communicate at all and therefore is able to partake in command & control processes).

Having said this, the same example utilized by Ford shows inconsistency at several places:

- Intel.ISR.Detect.Blue(R) for the AOC is set to “1” and should have resulted in Intel.ISR.Detect(R), Intel.ISR(R) and Intel(R) being characterized as present as well.
- Fires.IO.InflOps.Mildec(T) and Fires.IO.InflOps(T) for IADS1 and IADS2 are set to “1” and should have resulted in Fires.IO(T) be characterized as present as well.
- Fires.IO.InflOps.Mildec(R) and Fires.IO.InflOps(R) for ISR,AOC and PSP are set to “1” and should have resulted in Fires.IO(R) and Fires(R) be characterized as present as well.

Application of these findings to the Ford examples results in a different SEAD instantiation ∑ (see Table A4.1) and in conclusion in an apparent different interoperability measurement (sees Table A4.2).

Table A4.1. Applied consistency changes to SEAD instantiation ∑ (after 6:88)

	transmit						receive					
	HB	ISR	AOC	PSP	IADS1	IADS2	HB	ISR	AOC	PSP	IADS1	IADS2
C2	1	1	1	1	1	1	1	1	1	1	1	1
C2.Comm	1	1	1	1	1	1	1	1	1	1	1	1
C2.Comm.Blue	1	1	1	1	0	0	1	1	1	1	0	0
C2.Comm.Blue.Target	0	1	1	0	0	0	0	0	1	1	0	0
C2.Comm.Red	0	0	0	0	1	1	0	1	0	0	1	1
Intel	0	1	0	0	1	1	0	0	1	1	1	1
Intel.ISR	0	1	0	0	1	1	0	0	1	1	1	1
Intel.ISR.Detect	0	1	0	0	1	1	0	0	1	1	1	1
Intel.ISR.Detect.Blue	0	1	0	0	1	1	0	0	1	1	0	0
Intel.ISR.Detect.Red	0	1	0	0	0	0	0	0	0	0	1	1
Fires	0	0	0	1	1	1	0	1	1	1	1	1
Fires.CA	0	0	0	1	1	1	0	0	0	1	1	1
Fires.CA.OCA	0	0	0	1	0	0	0	0	0	1	1	1
Fires.CA.OCA.Ground	0	0	0	1	0	0	0	0	0	0	1	1
Fires.CA.OCA.Ground.Cluster	0	0	0	1	0	0	0	0	0	0	1	1
Fires.CA.OCA.Ground.Precision	0	0	0	0	0	0	0	0	0	0	1	1
Fires.CA.DCA	0	0	0	0	1	1	0	0	0	0	1	1
Fires.IO	0	0	0	0	1	1	0	1	1	1	1	1
Fires.IO.EW	0	0	0	0	0	0	0	0	0	0	1	1
Fires.IO.EW.EA	0	0	0	0	0	0	0	0	0	0	1	1
Fires.IO.EW.EA.Barrage	0	0	0	0	0	0	0	0	0	0	1	1
Fires.IO.EW.EA.Reactive	0	0	0	0	0	0	0	0	0	0	1	1
Fires.IO.InflOps	0	0	0	0	1	1	0	1	1	1	0	0
Fires.IO.InflOps.MILDEC	0	0	0	0	1	1	0	1	1	1	0	0
Movement&Maneuver	0	0	0	0	0	0	0	0	0	0	0	0
Protection	0	0	0	0	0	0	0	0	0	0	0	0
Sustainment	0	0	0	0	0	0	0	0	0	0	0	0

Table A4.2. Directional interoperability measurements after consistency changes

	HB	ISR	AOC	PSP	IADS1	IADS2
HB	0	1/9	1/9	1/9	2/27	2/27
ISR	1/9	0	8/27 (1/9)	8/27	2/9	2/9
AOC	1/9	1/9	0	4/27	2/27	2/27
PSP	1/9	4/27 (1/27)	4/27 (1/27)	0	7/27	7/27
IADS1	2/27	7/27 (2/27)	10/27 (5/27)	11/27 (1/27)	0	10/27 (1/27)
IADS2	2/27	7/27 (2/27)	10/27 (5/27)	11/27 (1/27)	10/27 (1/27)	0

Analyzing Table 4.2, the overall picture remains the same. Still the adversary IADS seems to be more capable than the blue PSP: I_c(PSP, IADS) = 7/27 < I_c(IADS, PSP) = 11/27). The change in value of 1/27 is deemed marginal and therefore of no real concern. On the other hand, the interoperability measurements for IADS on the red side and ISR and AOC on the blue side show different results. The advantage of ISR over IADS (I_o(ISR, IADS) = 6/27 > I_o(IADS, ISR) = 5/27) has flipped in favor of the red IADS (I_c(ISR, IADS) = 6/27 < I_c(IADS, ISR) = 7/27). For the relationship between AOC and IADS the superiority of IADS has even doubled (I_o(IADS, AOC) = 5/27 is now I_c(IADS, AOC) = 10/27) giving it an ample margin of 8/27 instead of only 3/27.

A similar picture can be derived from further analyzing the second example on an upgraded SEAD (see Table A4.3 and Table A4.4). Here the system's architecture was changed due to the addition of special capabilities to the PSP. While the relationships between ISR and AOC on the blue side and IADS on the red side prove a similar effect as described before, the effects (i.e. their interoperability) of IADS on PSP now hint towards an even less degree than before, suggesting that the additional capabilities might have more impact on IADS than anticipated (I_o(IADS, PSP) = 9/27 is now just I_c(IADS, PSP) = 7/27, giving PSP a margin of 5/27 instead of just 3/27 over IADS).

Table A4.3. Upgraded SEAD instantiation $\sum_U$ after consistency changes (after 6:91)

	transmit						receive					
	HB	*ISR*	*AOC*	*PSP*	*IADS1*	*IADS2*	*HB*	*ISR*	*AOC*	*PSP*	*IADS1*	*IADS2*
C2	1	1	1	1	1	1	1	1	1	1	1	1
C2.Comm	1	1	1	1	1	1	1	1	1	1	1	1
C2.Comm.Blue	1	1	1	1	0	0	1	1	1	1	0	0
C2.Comm.Blue.Target	0	1	1	0	0	0	0	0	1	1	0	0
C2.Comm.Red	0	0	0	0	1	1	0	1	0	0	1	1
Intel	0	1	0	0	1	1	0	0	1	0	1	1
Intel.ISR	0	1	0	0	1	1	0	0	1	0	1	1
Intel.ISR.Detect	0	1	0	0	1	1	0	0	1	0	1	1
Intel.ISR.Detect.Blue	0	1	0	0	1	1	0	0	1	***0***	0	0
Intel.ISR.Detect.Red	0	1	0	0	0	0	0	0	0	0	1	1
Fires	0	0	0	1	1	1	0	1	1	1	1	1
Fires.CA	0	0	0	1	1	1	0	0	0	1	1	1
Fires.CA.OCA	0	0	0	1	0	0	0	0	0	1	1	1
Fires.CA.OCA.Ground	0	0	0	1	0	0	0	0	0	0	1	1
Fires.CA.OCA.Ground.Cluster	0	0	0	1	0	0	0	0	0	0	1	1
Fires.CA.OCA.Ground.Precision	0	0	0	***1***	0	0	0	0	0	0	1	1
Fires.CA.DCA	0	0	0	0	1	1	0	0	0	0	1	1
Fires.IO	0	0	0	***1***	1	1	0	1	1	1	1	1
Fires.IO.EW	0	0	0	***1***	0	0	0	0	0	0	1	1
Fires.IO.EW.EA	0	0	0	***1***	0	0	0	0	0	0	1	1
Fires.IO.EW.EA.Barrage	0	0	0	***1***	0	0	0	0	0	0	***0***	***0***
Fires.IO.EW.EA.Reactive	0	0	0	***1***	0	0	0	0	0	0	1	1
Fires.IO.InflOps	0	0	0	0	1	1	0	1	1	1	0	0
Fires.IO.InflOps.MILDEC	0	0	0	0	1	1	0	1	1	1	0	0
Movement&Maneuver	0	0	0	0	0	0	0	0	0	0	0	0
Protection	0	0	0	0	0	0	0	0	0	0	0	0
Sustainment	0	0	0	0	0	0	0	0	0	0	0	0

Table A4.4. Directional interoperability measurements for the upgraded SEAD instantiation after consistency changes

	HB	ISR	AOC	PSP	IADS1	IADS2
HB	0	1/9	1/9	1/9	2/27	2/27
ISR	1/9	0	8/27 (1/9)	4/27 (-1/9)	2/9	2/9
AOC	1/9	1/9	0	4/27	2/27	2/27
PSP	1/9	5/27 (2/27)	5/27 (2/27)	0	4/9	4/9
IADS1	2/27	7/27 (2/27)	10/27 (5/27)	7/27 (-2/27)	0	10/27 (1/27)
IADS2	2/27	7/27 (2/27)	10/27 (5/27)	7/27 (-2/27)	10/27 (1/27)	0

To be clear, it is not the bare numbers that should attract the impact of keeping consistency in the instantiation of interoperability characters. Focus should rather be guided towards the relative change in numbers and the thorough analysis of each system pair's interoperability measurement.

The resulting character set never the less should pass through all chosen levels from bottom to the top to assign weight to a given capability at a lower level, i.e. higher degree of capability. For example the characters C2 and C2.Comm show no difference at all over all systems chosen (all are set to "1"). To dispose of one of the two characters (the highest level character C2 would seem to be the logical choice) or even both (since the systems are exclusively defined in their character states at the lower 3rd and 4th level already) would seem appropriate but would in the same instance diminish the fact that the systems are interoperating at a higher degree.

The consistency from lower levels to higher levels in the chosen character hierarchy, as well as keeping higher levels to ensure weighing of higher degrees of interoperability, has been applied in the present work.

Independence of interoperability measurement from system quantities

In order to find broad understanding in the group's effort of applying Ford's methodology on interoperability measurement it was necessary to evaluate possible side effects of the number of systems in a given architecture on the resulting interoperability measurement. Looking at Ford's example on SEAD (6:81-92), it could not clearly be understood why two adversary IADS systems (IADS1 and IADS2) were instantiated but only one friendly (blue) system each (HB, ISR, AOC, PSP). Neither the text nor the

graphs provided were able to answer the question. Therefore the group analyzed a different architecture by simply deleting IADS2 from the set of systems and recalculating the interoperability measurement (see Table A4.5).

Table A4.5. Directional interoperability measurements with only one IADS

	HB	ISR	AOC	PSP	IADS1
HB	0	1/9	1/9	1/9	2/27
ISR	1/9	0	5/27	8/27	2/9
AOC	1/9	1/9	0	4/27	2/27
PSP	1/9	1/9	1/9	0	7/27
IADS1	2/27	5/27	5/27	10/27	0

The individual interoperability measures are identical to the ones calculated with an instantiated second IADS2. This supports the suggestion that the number of systems has no influence whatsoever on the interoperability measurement as long as their individual character sets are identical. Should it be found desirable to evaluate a certain architecture that includes a system pair that is identical in most of its characters but a few, then these systems should be included separately. The slightest difference in their character sets (resulting out of technical, procedural or operational requirements) should be thoroughly analyzed and described by a different character at some place.

A5. Arena Discrete Event Simulation

This appendix provides more detail for readers interested in the Arena discrete event simulation. There are two pieces of the code description for each experimental component: a table summarizing various explanations and figures of the actual code.

1. Discrete event experimental component that provides MOEs not related to interoperability measurements (mission resource component)

Initialize Variables (read from file)

- Arena® accesses the file "LS input.xls", located in the same folder as the simulation model
- The following values are read assigned to variables for later use within the simulation process:

▪ read day and night influence and daylight times:	simulation will ignore nighttime if value is set to '0' start of daylight [hrs] end of daylight [hrs]	v_day_night(1,1) v_day_night(1,2) v_day_night(1,3)
▪ read weather influence:	simulation will ignore bad weather if value is set to '0'; if set to value other than '0' bad weather will prohibit use of E/O and IR sensors	v_weather
▪ read random event:	currently disabled (might be used to generate an event later in the simulation)	v_random_event
▪ read grid parameters:	gridsize (number of rows and columns) keypad size (side length of one keypad element in km)	v_gridsize_rows v_gridsize_columns v_keypad_size
▪ read coverage limit:	desired maximum number of systems assigned to cover an event	v_aircraft_limit
▪ read distances:	distance from homebase to AOR entry point distance from CAOC to AOR (to enforce BLOS	v_distances(1,1) v_distances(2,1)

	dependence)	
▪ read system names:	currently disabled, since string functions in Arena could not be utilized sufficiently	v_system_name(x,1)
▪ read system designator:	system designator number {1, 2, 3, 4, 5}; system designator will be used sub sequentially in order to address a certain system's attributes (x)	v_aircraft_type
▪ read number of systems:	total number of systems of a certain type	v_number_of_systems(x, 1)
▪ read number of systems at homebase:	number of systems that will be stationed at homebase at start of simulation run	v_number_of_systems(x, 2)
▪ read system speeds:	cruise speed of a system (not loiter speed); required to determine transition times between homebase and AOR)	v_speed(x,1)
▪ read maximum mission times	overall mission time of a specific system	v_loiter_time(x,1)
▪ read E/O sensor capability	a given system's E/O capability	v_sensor_type(x,1)
▪ read IR sensor capability	a given system's IR capability	v_sensor_type(x,2)
▪ read SAR sensor capability	a given system's SAR capability	v_sensor_type(x,3)
▪ read sensor footprint radius	sensor footprint (radius, in km) on the ground; if two or more sensors are available for a certain system, the maximum footprint should be provided	v_sensor_footprint(x,1)
▪ read SATCOM capability (BLOS)		v_satcom_capable(x,1)
▪ read VOICE communications capability (LOS)		v_voice_capable(x,1)
▪ read aircraft reliability	reliability value for the aircraft	v_reliability(x,1)
▪ read sensor	reliability value for the	v_reliability(x,2)

reliability	sensor	
▪ read communications equipment reliability	reliability value for the communications equipment	v_reliability(x,3)
▪ read nighttime operations capability	system's capability to operate at nighttime (sensor and/or aircraft)	v_night_ops(x,1)

Create Event (location, day/night, weather)

- The simulation will initially determine an event that happens at a random hour (full hour between start of daylight and one hour before daylight ends); this approach was chosen to allow for reaction time to reassign E/O systems to cover the event. The random event location (keypad row and column) will be selected as well.
- Chances for bad weather influence will be specified using the user input as percentage value.
- The initially generated systems are called to 'fill' the AOR (see below).
- Depending on the current hour (daytime or nighttime) and weather condition, the actual sensor requirements to cover an event are determined.
- The sequence elapses full hours to set the mission clock.

Create Systems & Assign Attributes

- Initial generation of systems (up to five) and respective numbers as specified by user on input sheet (total # of systems)
- Assigning system attributes
- Split of systems: station user defined number of systems on homebase, the others are deployed into AOR (held in 'AOR Airborne Aircraft' queue until called by 'Create Event' logic)
- Mission attributes will be assigned to AOR aircraft (decrease of a_time_to_joker; resembles that aircraft have already been on station for a while before event happens)
- Aircraft will be assigned to event unless limit has been reached
    - Aircraft that are already within sensor reach of the event will start coverage of the event immediately
    - Aircraft that are out of reach of the event will be reassigned to the event (closest aircraft first); travel time to transition from current location to event location will elapse before event coverage begins

Actions at Homebase

- Aircraft are assigned to a specific holding spot (shelter) at homebase according to their system designator number
- Returning aircraft (out of AOR) will require turn-around time before they become available for further assignments; aircraft that returned to homebase due to a

failure will require additional turn-around time for repairs

- Aircraft launches can happen due to a specific CAOC decision or as a regular replacement
    - Regular replacement:
        - mission parameters (assigned to event or regular mission) are provided
        - in case system was not night ops capable and would not reach mission location before nightfall, launch will be aborted and CAOC receives notification to reconsider decision
    - CAOC decision:
        - mission parameters (assigned to event or regular mission) are provided
- Aircraft transitions from homebase to AOR entry point

Actions within Area of Responsibility (AOR)

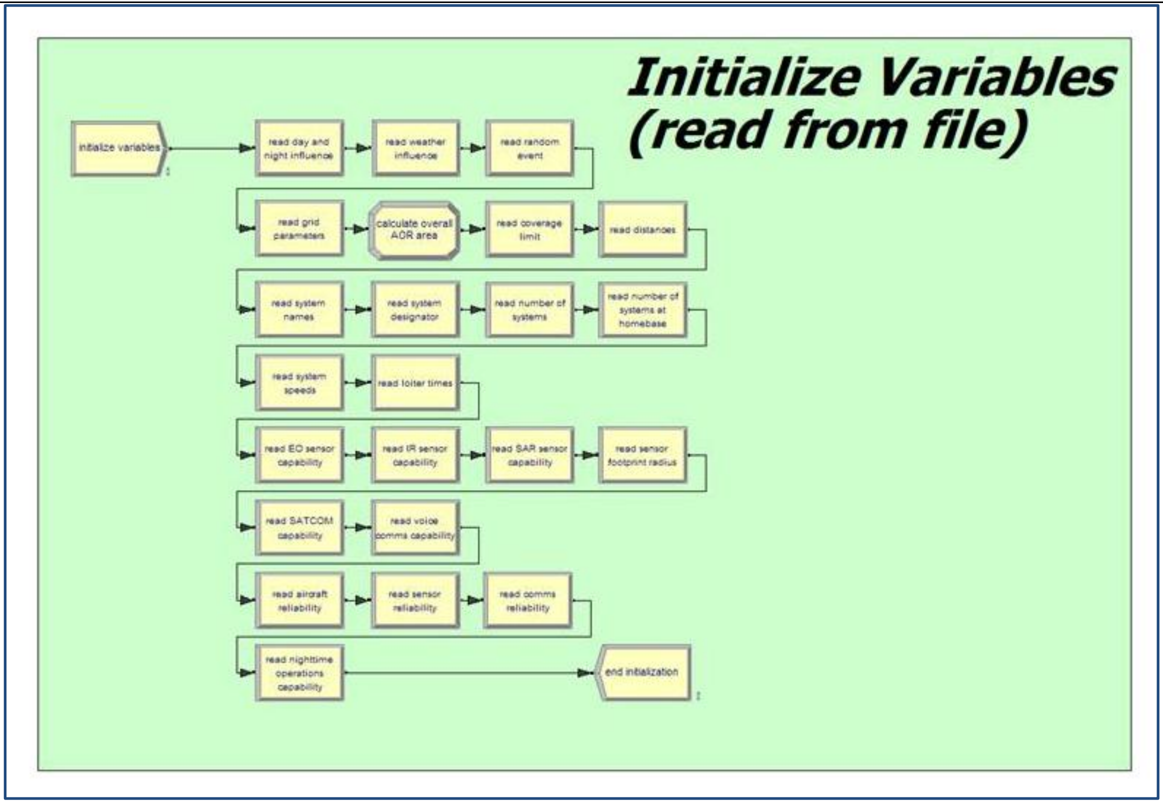
- Aircraft that reach AOR entry point (and initial deployments at run start) are handled according to their assignment status (assigned to event or regular mission)
- Aircraft transition between 'stations' according to travel time:
    - transition from entry point to mission area and back
    - reassignment from mission area to event location at run start
- Travel times are deducted from available mission time (time to joker = time at which a regular replacement needs to be called in to allow for seamless transfer of duties; time to joker is determined as 20% of overall mission time)
- Before entering the loiter 'stations' (over event or regular mission) the simulation checks for possible system failures (aircraft, sensor or communications equipment); if random failure gate trips, the failure code is recorded and time to joker reduced by random (understand as: the system knows beforehand whether or not it will malfunction)
- After joker time is reached, the procedure will determine the further progress before continuing mission until bingo time:
    - No failure:
      A regular replacement will be called in (same system type) if available; if not available, CAOC decision is required
    - Communications failure:
      system will continue its mission (gather data for later analysis) until reaching bingo time; replacement will be handled by CAOC decision (CAOC needs time to realize comms outage; see below)
    - Aircraft or sensor failure:
      system will abort its mission immediately; CAOC decision is required to handle replacement
- When bingo time is reached (or after immediate mission abort due to failure) the aircraft transitions to AOR entry point and from there to homebase for turn-around

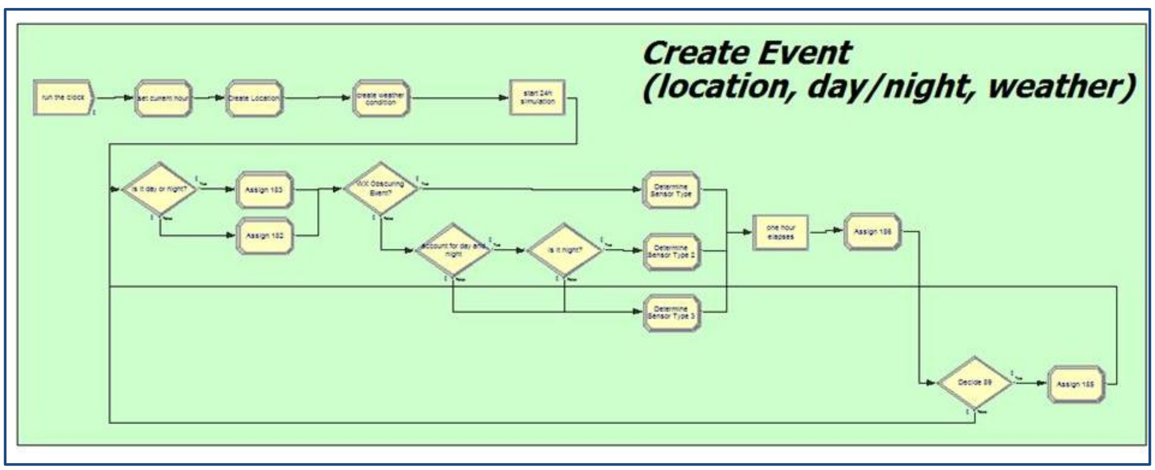
CAOC Decision Actions

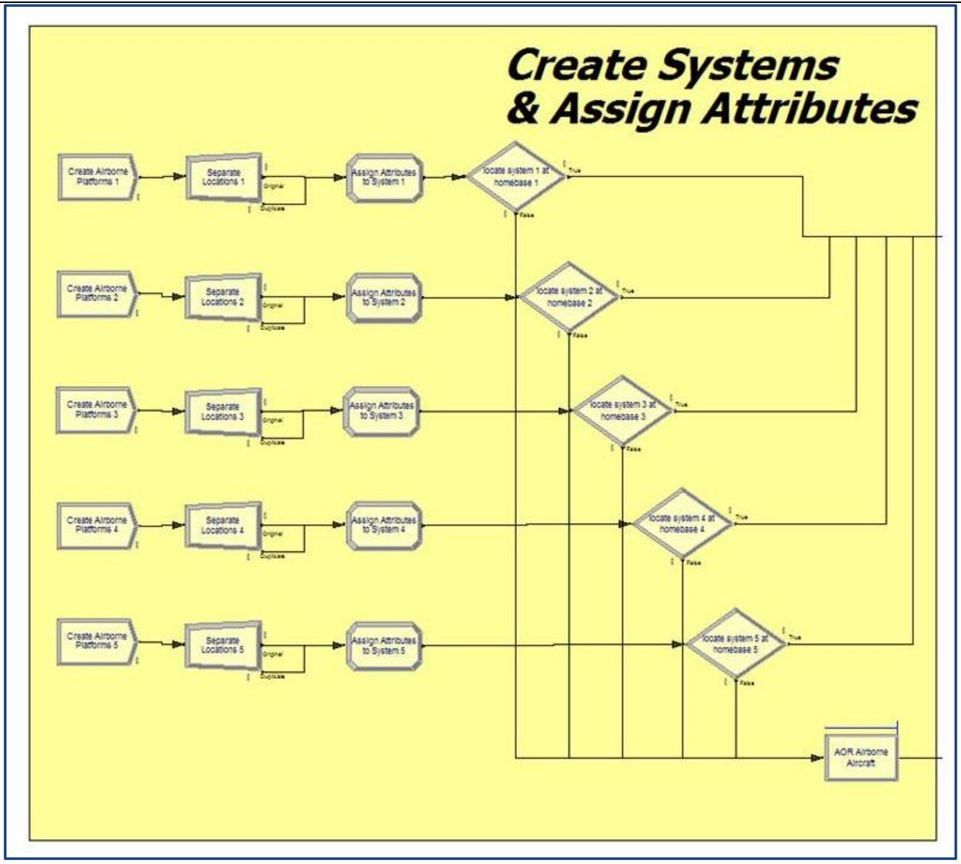
- CAOC decisions are required in all unforeseen events (launch abort, mission abort after failure, re-tasking if equivalent system is not available at homebase):
    - After called upon, time for decision process starts. Time for situation analysis (and realization of a comms failure) will be added
    - First choice is to replace an specific aircraft with the same type, if available
    - In case no systems are available at any homebase, time will be added for reconsideration before decision cycle starts again
    - Decision maker calls for another aircraft based on a availability (higher number of aircraft at a specific homebase increases its chances to be called upon)
    - Selected aircraft is checked for night ops or sufficient time before night ops would be required; if system does not fulfill night ops requirement then CAOC decision cycle will be reinitiated after a certain amount of reconsideration time
    - A successful decision process calls the appropriate system off its homebase and mission orders are transmitted
    - CAOC decision time is recorded in the end

Display Area

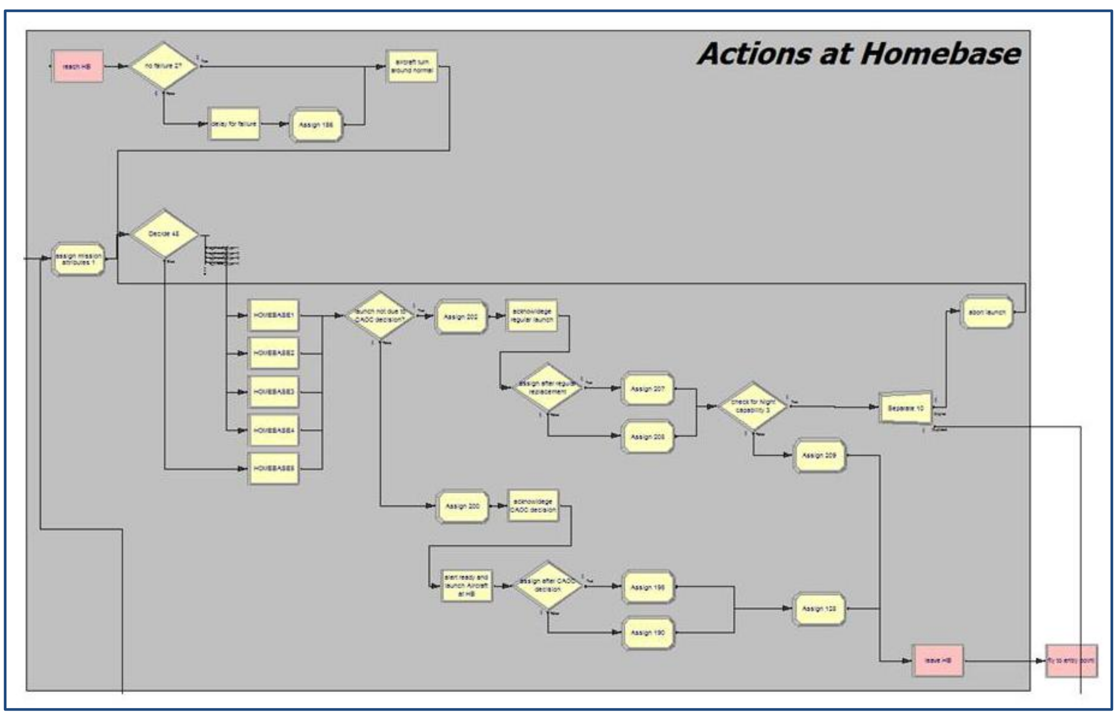
- Several approaches to display viable information on the run progress is provided:
    - Theater overview:
        - shows aircraft locations (at homebase, in transition, covering event, performing regular mission)
        - shows level of mission time left (to reach joker time or bingo time)
        - provides overall information on runtime, daytime, weather and number of aircraft
    - Plot areas:
        - Several observations are plotted over time:
            - number of aircraft assigned to event
            - number of aircraft covering event
            - number of aircraft in AOR
            - number of failures (aircraft, sensor, comms, overall)
            - covered area (overlapping coverage areas are NOT accounted for)


Initialize Variables
(read from file)
initialize variables
read day and night influence
read weather influence
read random event
read grid parameters
calculate overall AOR area
read coverage limit
read distances
read system names
read system designator
read number of systems
read number of systems at homebase
read system speeds
read loiter times
read EO sensor capability
read IR sensor capability
read SAR sensor capability
read sensor footprint radius
read SATCOM capability
read voice comms capability
read aircraft reliability
read sensor reliability
read comms reliability
read nighttime operations capability
end initialization

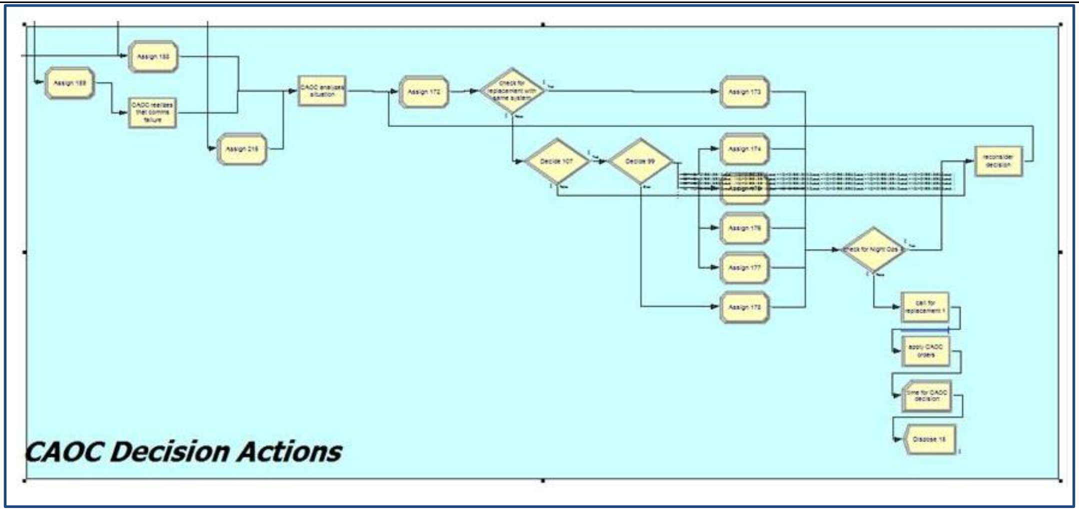

Create Event
(location, day/night, weather)

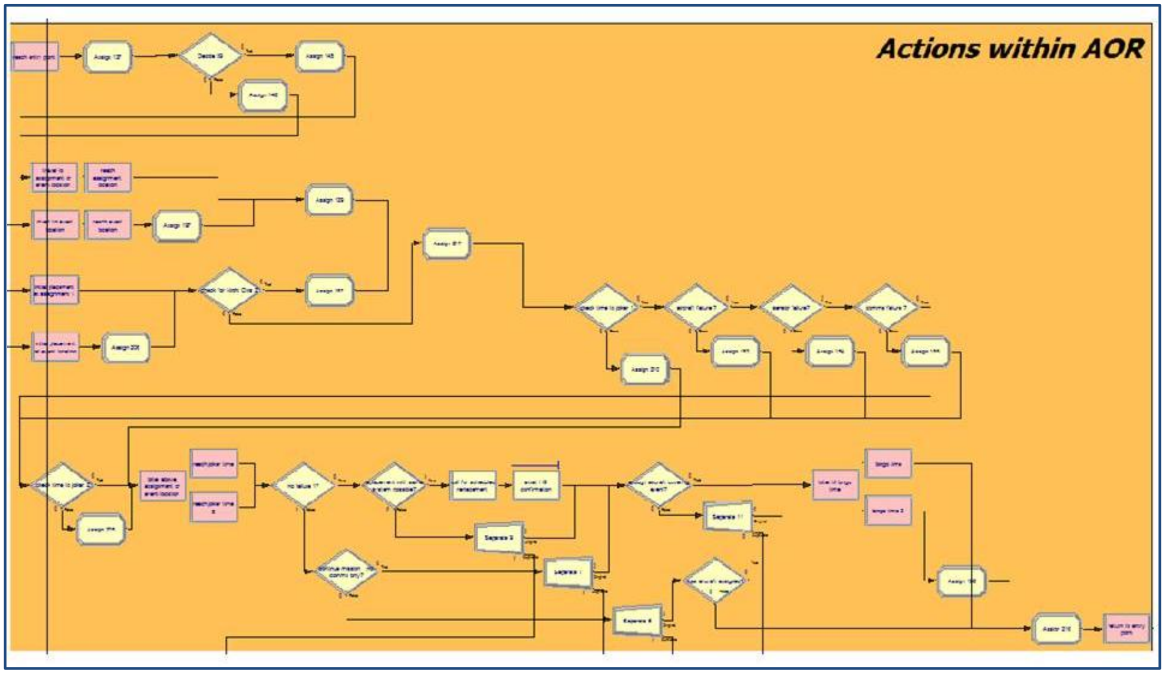


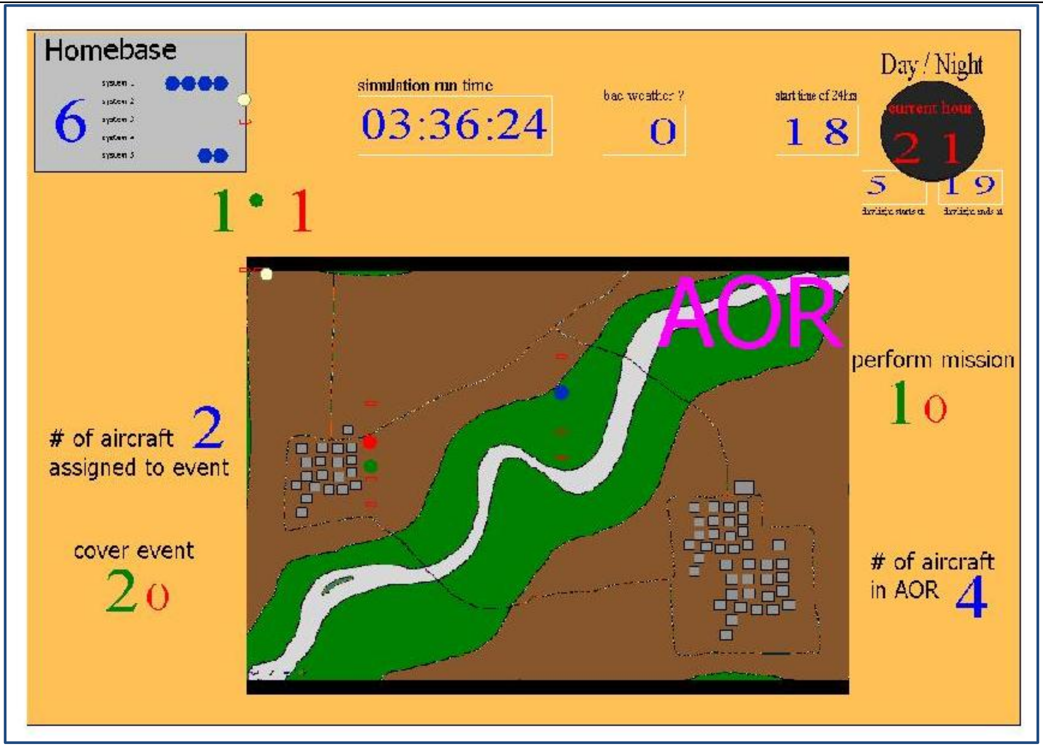
Create Systems
& Assign Attributes
Create Airborne Platforms 1
Separate Locations 1
Assign Attributes to System 1
locate system 1 at homebase 1
Create Airborne Platforms 2
Separate Locations 2
Assign Attributes to System 2
locate system 2 at homebase 2
Create Airborne Platforms 3
Separate Locations 3
Assign Attributes to System 3
locate system 3 at homebase 3
Create Airborne Platforms 4
Separate Locations 4
Assign Attributes to System 4
locate system 4 at homebase 4
Create Airborne Platforms 5
Separate Locations 5
Assign Attributes to System 5
locate system 5 at homebase 5
AOR Airborne Aircraft

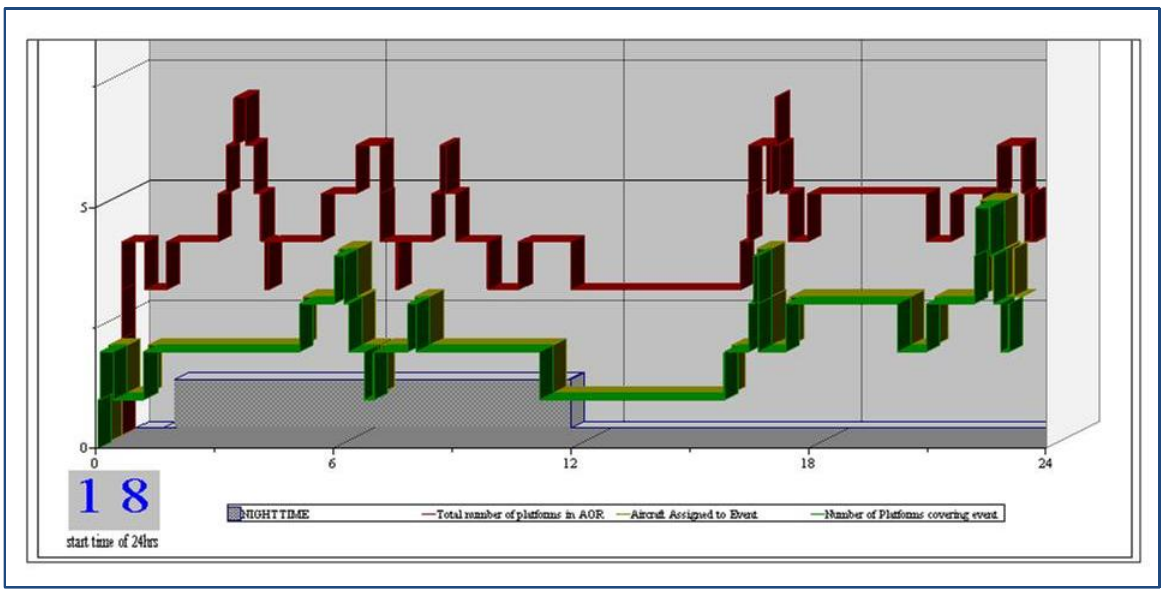


Actions at Homebase
HOMEBASE1
HOMEBASE2
HOMEBASE3
HOMEBASE4
HOMEBASE5


CAOC Decision Actions


Actions within AOR


Homebase
6
simulation run time
03:36:24
bad weather ?
0
start time of 24hrs
18
Day / Night
current hour
21
5
19
1 1
AOR
perform mission
1 0
# of aircraft assigned to event 2
cover event
2 0
# of aircraft in AOR 4


18
start time of 24hrs
NIGHTTIME
Total number of platforms in AOR
Aircraft Assigned to Event
Number of Platforms covering event

2. Discrete event experimental component that provides the MOE related to interoperability measurements (system interoperability component)

Initialize Variables (read from file)

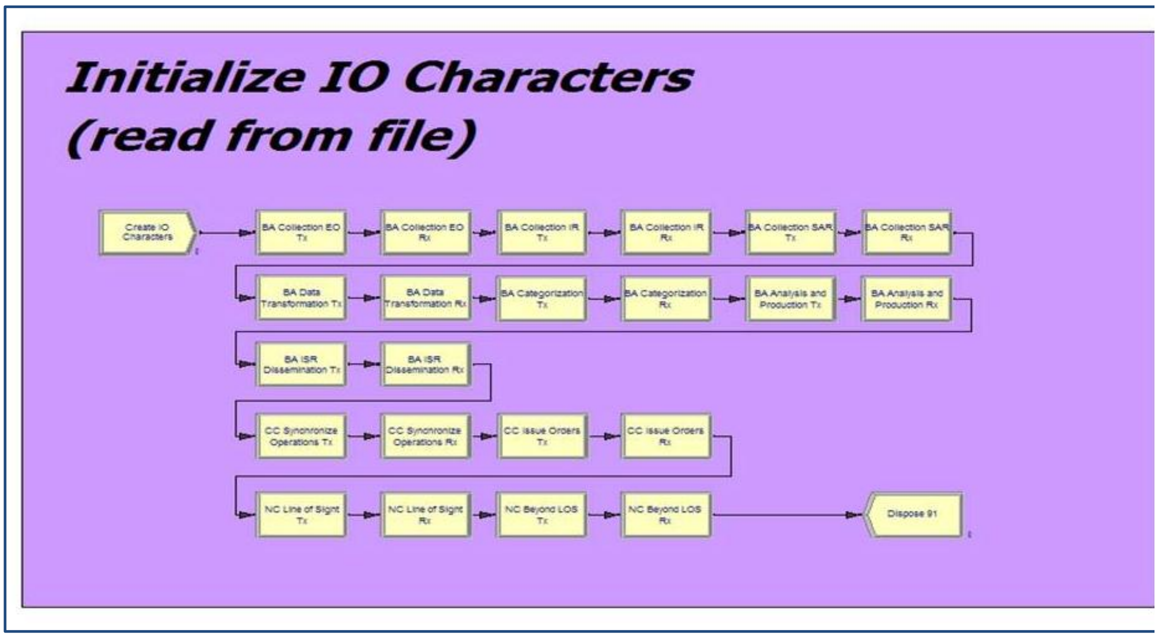
- Arena® accesses the file "JCA applied.xls", located in the same folder as the simulation model
- The following values are read assigned to variables for later use within the simulation process:

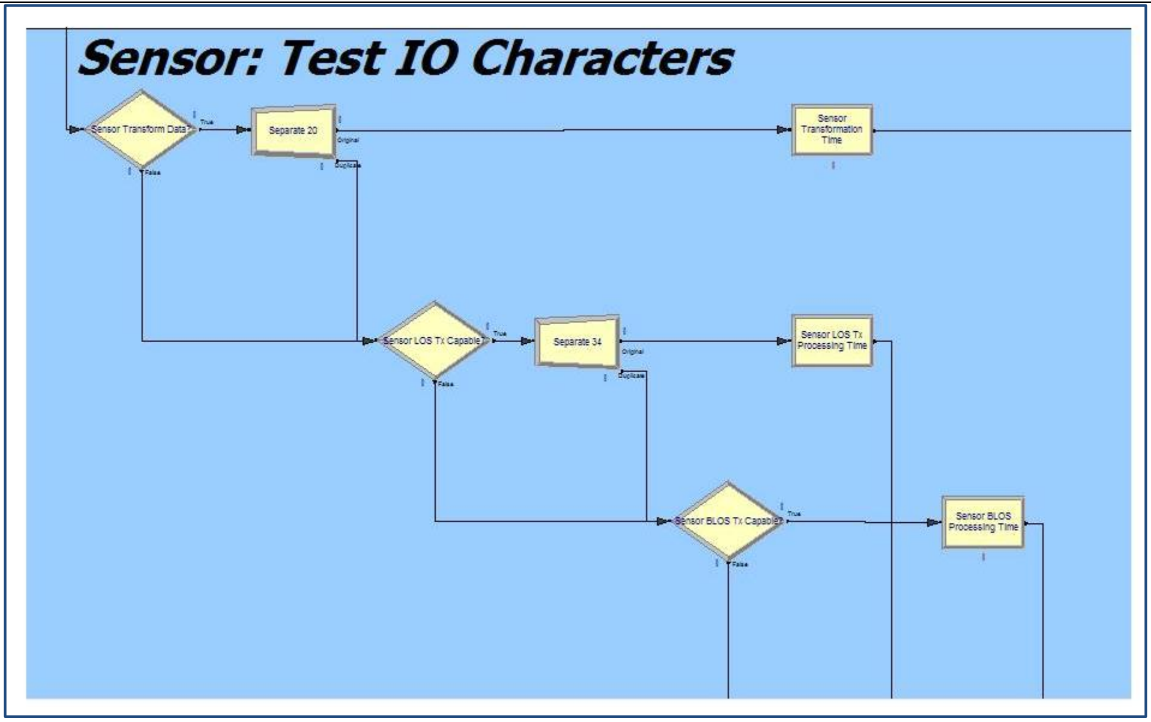
▪ read Battlespace Awareness data transformation (receive/transmit) IO character:	"0" or "1" defines IO character. BA refers to a separate input "Row" in the simulation	BA_Transform_Tx BA_Transorm_Rx
▪ read Battlespace Awareness categorization (receive/transmit) IO character:	"0" or "1" defines IO character. BA refers to a separate input "Row" in the simulation	BA_Categorization_Tx BA_Categorization_Rx
▪ read Battlespace Awareness collection (receive/transmit) IO characters:	"0" or "1" defines IO characters for either IR/E/O/SAR sensors. BA refers to a separate input "Row" in the simulation	BA_Collection_E/O_Tx BA_Collection_E/O_Rx BA_Collection_IR_Tx BA_Collection_IR_Rx BA_Collection_SAR_Rx BA_Collection_SAR_Tx
▪ read Battlespace Awareness analysis/production (receive/transmit) IO characters:	"0" or "1" defines IO character. BA refers to a separate input "Row" in the simulation	BA_Analysis_Tx BA_Analysis_Rx
▪ read Net-centric LOS (receive/transmit) IO characters:	0" or "1" defines IO character. NC refers to a separate input "Row" in the simulation	NC_LOS_Tx NC_LOS_Rx
▪ read Net-centric BLOS (receive/transmit) IO characters:	0" or "1" defines IO character. NC refers to a separate input "Row" in the simulation	NC_LOS_Tx NC_LOS_Rx

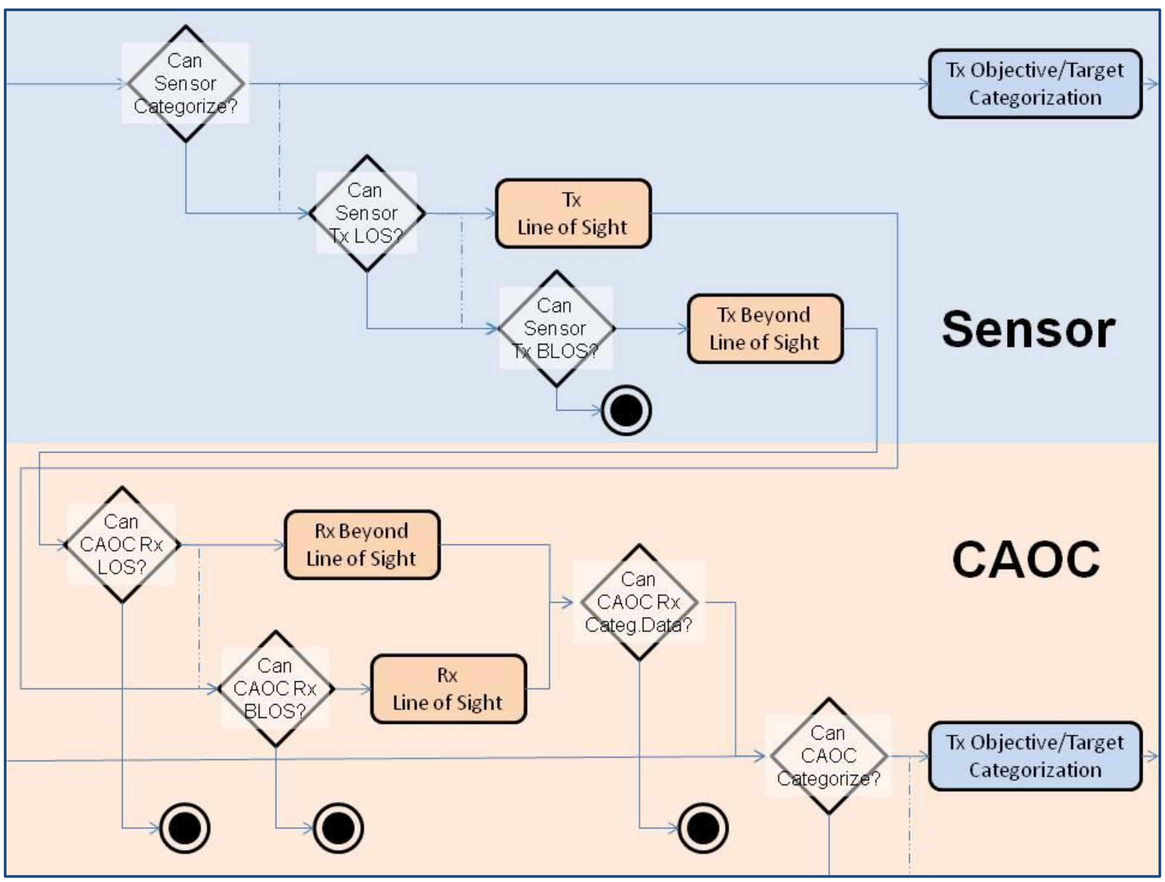
▪ read Command and Control (receive/transmit IO characters:	0" or "1" defines IO character. CC refers to a separate input "Row" in the simulation	CC_Issue_Orders_Rx CC_Issue_Orders_Tx

Results

- The Interoperability character simulation recorded two statistics: Record Number (number of paths for each entity) and the Record Time (total time for each entity). Instead of utilizing the software's statistical models available, the "Tools > ReportDatabase>Export Summary Statistics to CSV (comma separated values) file" function was utilized to export the data to a Microsoft® Excel® spreadsheet. These results are available in Chapter 3 and 4.



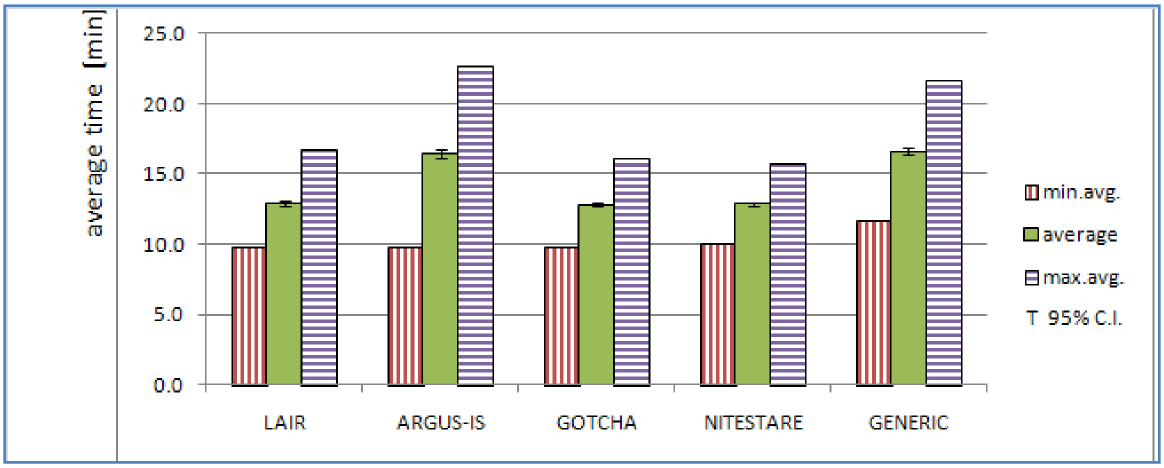

Sensor: Test IO Characters
Sensor Transform Data?
True
False
Separate 20
Original
Duplicate
Sensor Transformation Time
Sensor LOS Tx Capable?
True
False
Separate 34
Original
Duplicate
Sensor LOS Tx Processing Time
Sensor BLOS Tx Capable?
True
False
Sensor BLOS Processing Time

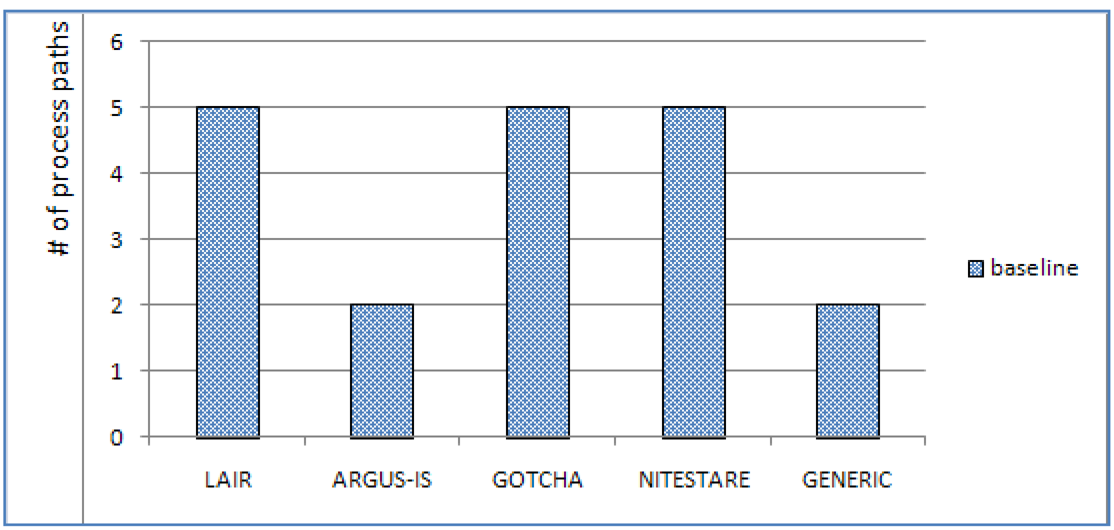

Can Sensor Categorize?
Tx Objective/Target Categorization
Can Sensor Tx LOS?
Tx Line of Sight
Can Sensor Tx BLOS?
Tx Beyond Line of Sight
Sensor
CAOC
Can CAOC Rx LOS?
Rx Beyond Line of Sight
Can CAOC Rx Categ.Data?
Can CAOC Rx BLOS?
Rx Line of Sight
Can CAOC Categorize?
Tx Objective/Target Categorization

A6. Complete Collection of System Interoperability Experimental Results

Baseline for Interoperability Experiment (IE) Test Plan

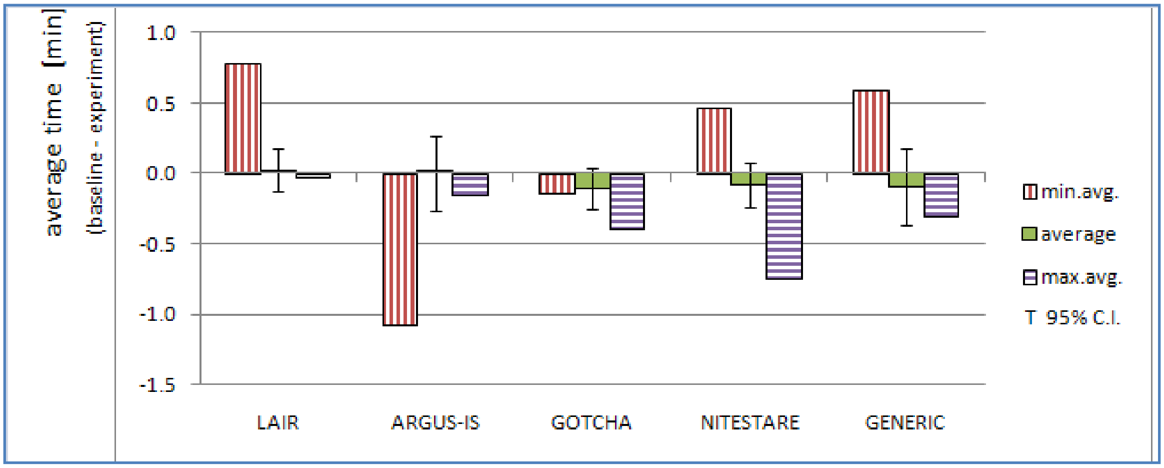
	LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
ARGUS-IS	5/12	0	1/3	5/12	11/24	**7/12**	**7/12**
GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
NITESTARE	13/24	7/12	1/2	0	7/12	**5/8**	**19/24**
GENERIC	5/12	11/24	3/8	5/12	0	**5/8**	**7/12**
CAOC	**5/12**	**5/12**	**5/12**	**5/12**	**11/24**	**0**	**5/8**
GF	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**0**

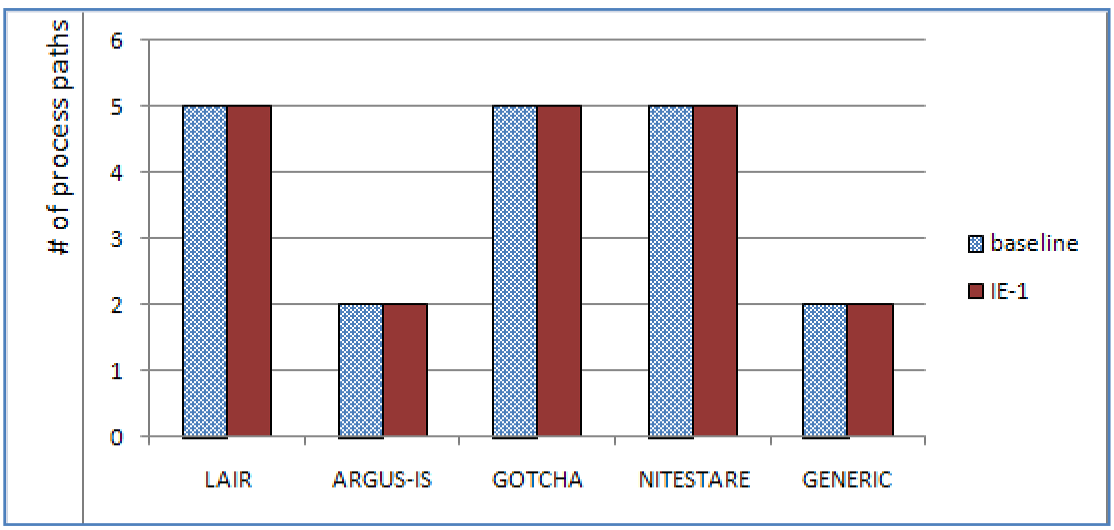




Experiment IE-1 (add IR sensor to ARGUS-IS)

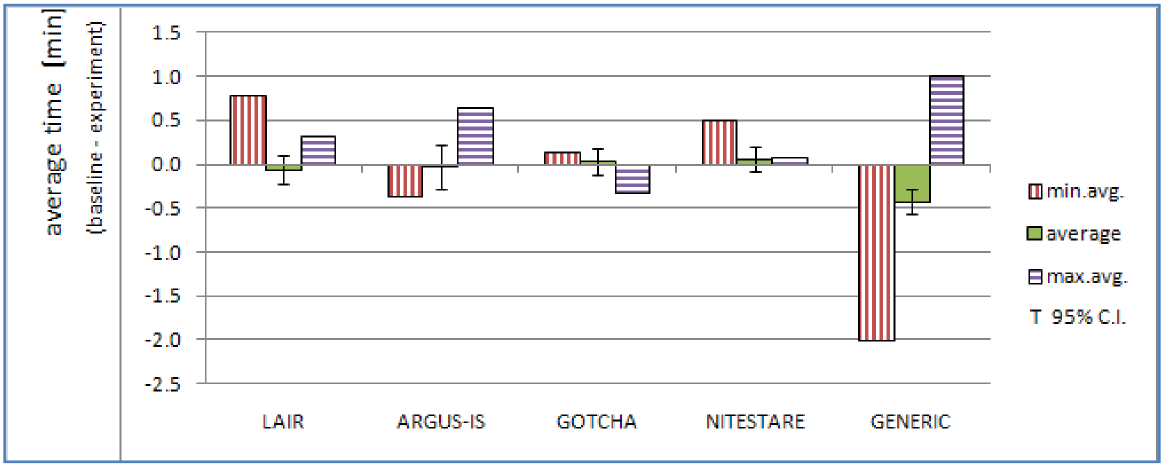
	LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
ARGUS-IS	5/12	0	1/3	5/12 (1/24)	11/24 (1/24)	**7/12 (1/24)**	**7/12 (1/24)**
GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
NITESTARE	13/24	7/12 (1/24)	1/2	0	7/12	**5/8**	**19/24**
GENERIC	5/12	11/24 (1/24)	3/8	5/12	0	**5/8**	**7/12**
CAOC	**5/12**	**5/12**	**5/12**	**5/12**	**11/24**	**0**	**5/8**
GF	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**0**

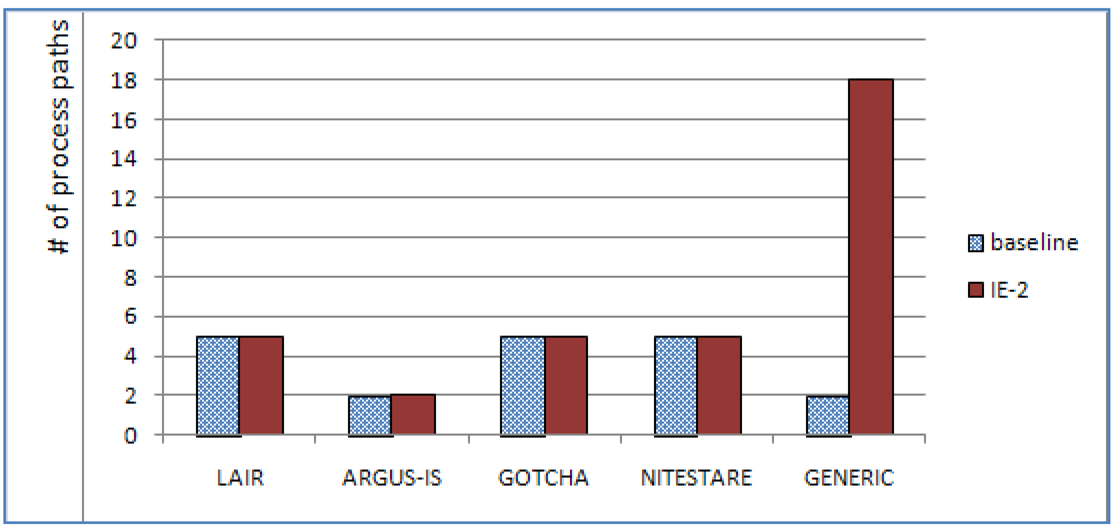




Experiment IE-2 (add BLOS capability to GF)

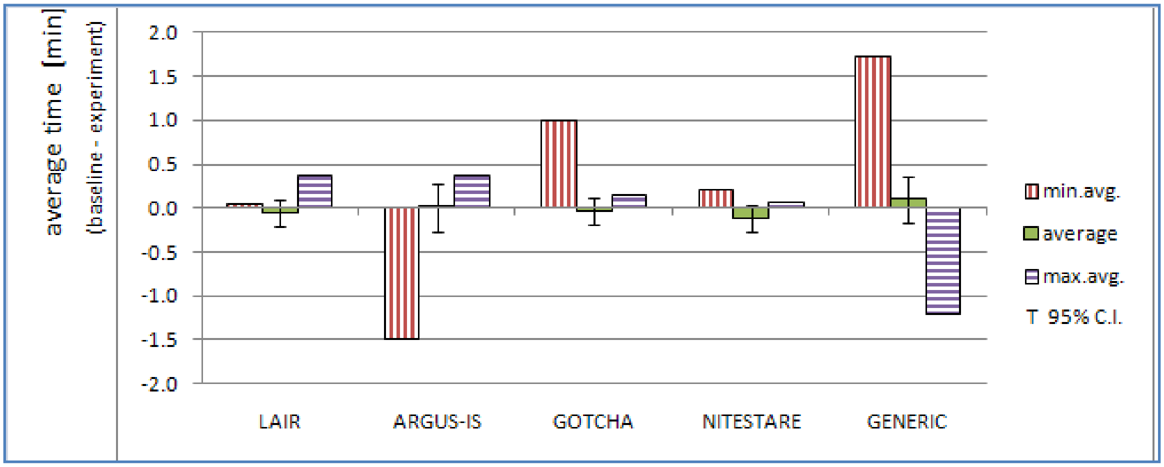
	LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
ARGUS-IS	5/12	0	1/3	3/8	5/12	**13/24**	**13/24**
GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
NITESTARE	13/24	13/24	1/2	0	7/12	**5/8**	**19/24**
GENERIC	5/12	5/12	3/8	5/12	0	**5/8**	**5/8 (1/24)**
CAOC	**5/12**	**5/12**	**5/12**	**5/12**	**11/24**	**0**	**2/3 (1/24)**
GF	**5/12**	**5/12**	**5/12**	**5/12**	**11/24 (1/24)**	**11/24 (1/24)**	**0**

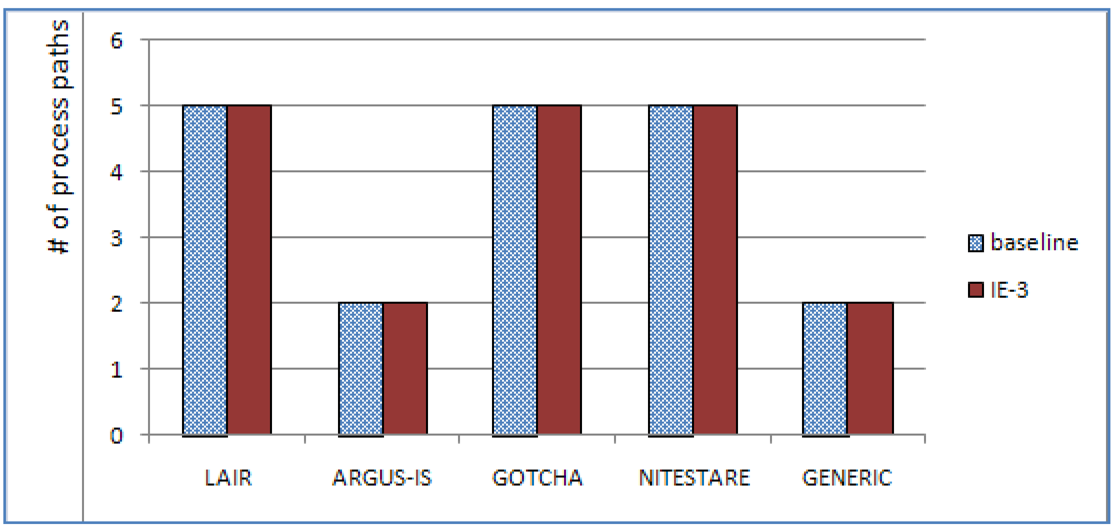




Experiment IE-3 (add BLOS capability to ARGUS-IS)

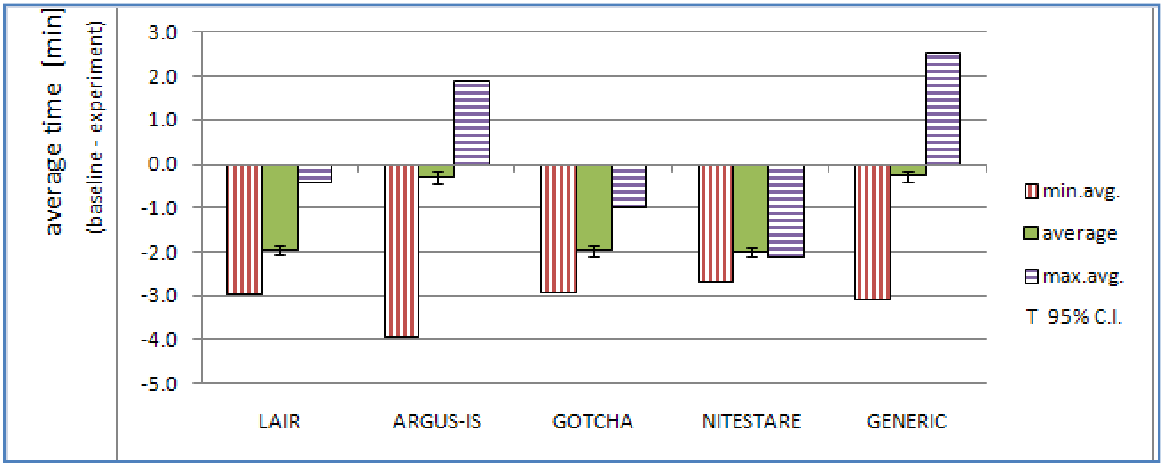
	LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
ARGUS-IS	5/12	0	1/3	3/8	11/24 (1/24)	**7/12 (1/24)**	**13/24**
GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
NITESTARE	13/24	13/24	1/2	0	7/12	**5/8**	**19/24**
GENERIC	5/12	11/24 (1/24)	3/8	5/12	0	**5/8**	**7/12**
CAOC	**5/12**	**11/24 (1/24)**	**5/12**	**5/12**	**11/24**	**0**	**5/8**
GF	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**0**

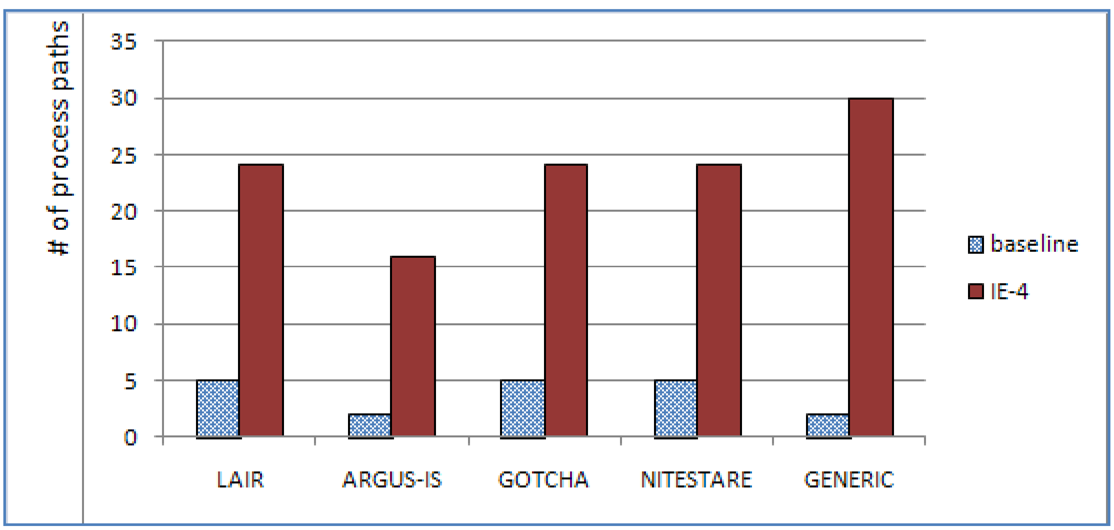




Experiment IE-4 (move CAOC within LOS of AOR)

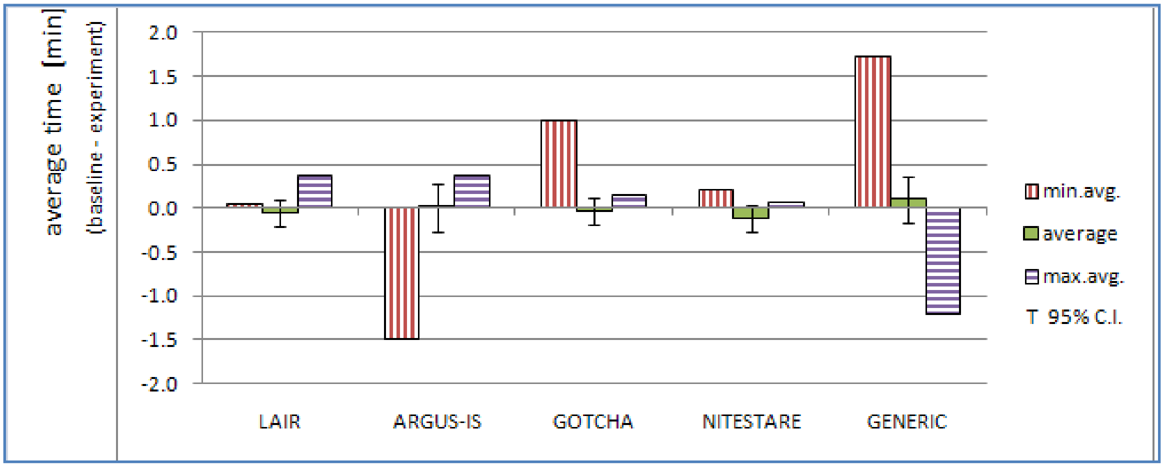
	LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
ARGUS-IS	5/12	0	1/3	3/8	5/12	**13/24**	**13/24**
GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
NITESTARE	13/24	13/24	1/2	0	7/12	**5/8**	**19/24**
GENERIC	5/12	5/12	3/8	5/12	0	**5/8**	**7/12**
CAOC	**5/12**	**5/12**	**5/12**	**5/12**	**11/24**	**0**	**5/8**
GF	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**0**

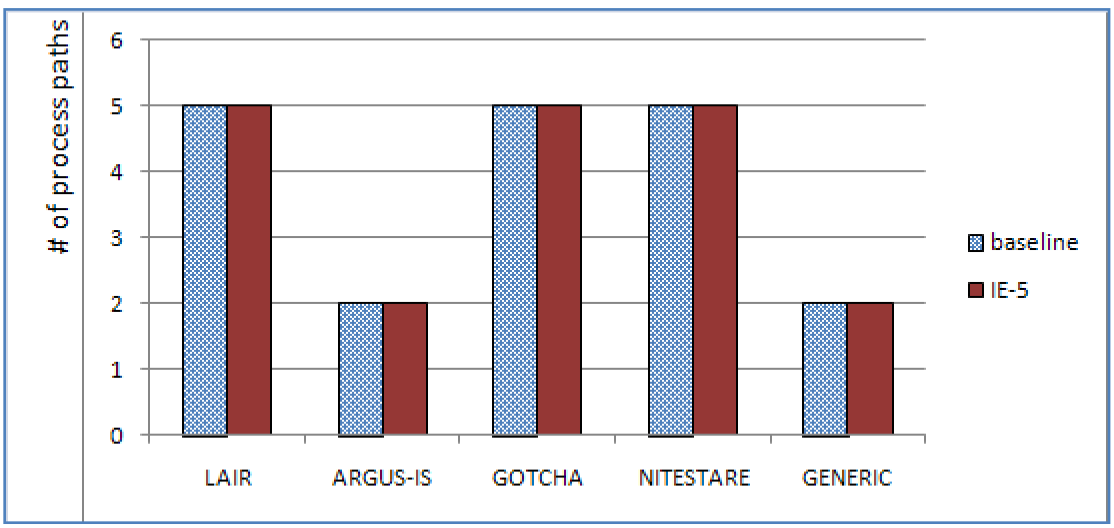




Experiment IE-5 (add IR sensor and BLOS capability to ARGUS-IS)

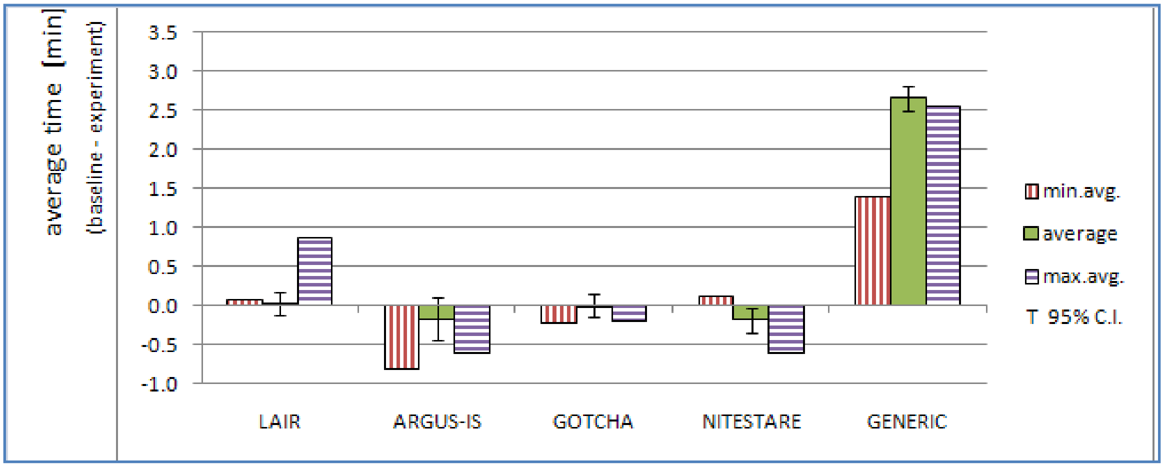
	LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
ARGUS-IS	5/12	0	1/3	5/12 (1/24)	1/2 (1/12)	**5/8 (1/12)**	**7/12 (1/24)**
GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
NITESTARE	13/24	7/12 (1/24)	1/2	0	7/12	**5/8**	**19/24**
GENERIC	5/12	1/2 (1/12)	3/8	5/12	0	**5/8**	**7/12**
CAOC	**5/12**	**11/24 (1/24)**	**5/12**	**5/12**	**11/24**	**0**	**5/8**
GF	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**0**

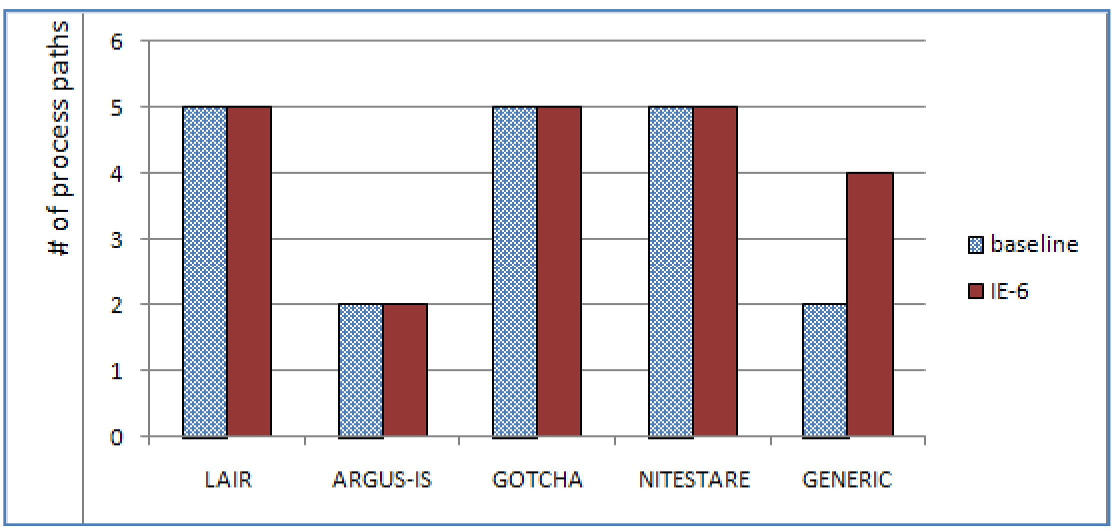




Experiment IE-6 (add ISR analysis/production and dissemination to GENERIC)

	LAIR	ARGUS-IS	GOTCHA	NITESTARE	GENERIC	CAOC	GF
LAIR	0	7/12	1/2	13/24	7/12	**5/8**	**19/24**
ARGUS-IS	5/12	0	1/3	3/8	5/12	**13/24**	**13/24**
GOTCHA	1/2	1/2	0	1/2	13/24	**13/24**	**17/24**
NITESTARE	13/24	13/24	1/2	0	7/12	**5/8**	**19/24**
GENERIC	5/12	5/12	3/8	5/12	0	**17/24 (1/12)**	**2/3 (1/12)**
CAOC	**5/12**	**5/12**	**5/12**	**5/12**	**11/24**	**0**	**5/8**
GF	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**5/12**	**0**





Bibliography

1. Bryant, Mike, Paul Johnson, Brian M. Kent, Michael Nowak, and Steve Rogers. *Layered Sensing: Its Definition, Attributes, and Guiding Principles for AFRL Strategic Technology Development,* Sensors Directorate White Paper, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, 1 May 2008.

2. Chairman of the Joint Chiefs of Staff. Joint Publication (JP) 1-02, *Department of Defense Dictionary of Military and Associated Terms.* Washington, DC. GPO, 2008.

3. Chairman of the Joint Chiefs of Staff. JP 2-01, *Joint and National Intelligence Support to Military Operations.* Washington, DC. GPO 2004

4. Chairman of the Joint Chiefs of Staff. JP 6-0, *Joint Communications System.* Washington, DC. GPO, 2006

5. Defense Technical Information Center. "Joint Capability Areas – Definitions." CJCS/J7. www.dtic.mil/futurejointwarfare/cap_areas.htm (12 Jan 2009).

6. Ford, Tom C. Interoperability Measurement, AFIT Dissertation AFIT/DSE/ENV/08-S01. August, 2008.

7. Mensh, Dennis Roy, Robert S. Kite, and Paul H. Darby. "The Quantification of Interoperability," *Naval Engineers Journal*. 251-259. May 1989.

8. Rockwell Automation. *Arena Basic Users Guide.* November 2007.

9. Rockwell Automation. *Arena Smart Files Library.* November 2007.

10. Susan Milton and Jesse C. Arnold, *Introduction to Probability and Statistics, 4th. Edition* (Boston, MA, McGraw Hill, 2003), 336 – 349, 700.

Vita

Lieutenant Colonel Jan von der Felsen, DEUAF

Lieutenant Colonel Jan von der Felsen graduated from the Bundeswehr University in Munich, Germany with the academic degree of Diplom-Ingenieur Univ. in Aerospace Engineering in 1994. He has spent 21 years in the German Air Force and was assigned to several operational and commanding positions related to ground based air defense systems. His experience includes weapon system training and simulation as well as concept development and experimentation.

Major Darryl L Insley, USAF

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Brian McKellar has had various collegiate experiences dating back to 1986. He has studied at Michigan State University, Florida State University, and the Air Force Institute

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
18-06-2009	Graduate Research Paper	Sep 2008 – Jun 2009

4. TITLE AND SUBTITLE

Linking Interoperability Characters and Measures of Effectiveness: A Methodology for Evaluating Architectures

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)

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8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/ISE/ENV/09-J01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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WPAFB, OH 45433-7321

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RYAA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT The Air Force Research Laboratory's Sensors Directorate has crafted a long-term layered sensing project and seeks a method to compare different architectural representations. This research provides an executable methodology for quantitative architecture comparisons based on interoperability characters and measurements. The methodology has two components and is demonstrated on an urban operations mission thread scenario. The layered sensing scenario requires sensor-equipped platforms to shift orbits while supporting a mission (e.g. supply convoy) reacting to unplanned events (e.g. improvised explosive device). The first component is a discrete event simulation capturing relevant sensor, platform, and mission operations and providing measures of effectiveness (MOEs) and measures of performance (MOPs). The second component is an application of a general purpose interoperability measurement technique applied to a scenario demonstrating collaborative interoperability. The results from experimental component comparisons show that changes in interoperability measurements do not always reflect the magnitude of changes in mission effectiveness or system performance. For net-centric applications, changes in the number of process paths may be a better indicator for the degree of interoperability present in a given architecture.

15. SUBJECT TERMS

Layered Sensing, Interoperability, Interoperability Measurement, Measure of Effectiveness, Process Path

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Dr. David R. Jacques, AFIT/ENV
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